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A DISSERTATION

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CHEMICAL ENGINEERING

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

BY

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ABSTRACT

The possibility of reducing crude oil pipeline pressure gradients by the addition of water to the flowing oil suggests the need for further fundamental knowledge on the flow characteristics of oil in the presence of water.

The flow of three oils of viscosities 6.29, 15.6 and 65.0 cp. in the presence of water was studied in a horizontal pipeline of 1.040 inches internal diameter. The densities of the oils and water were equal.

Flow patterns were noted for a range of superficial oil velocity from 0.05 to 3.0 ft. per sec. and a range of superficial water velocity from 0.1 to 3.5 ft. per sec. with oil-water input ratios from 0.1 to 10.0. At high superficial oil velocities oil formed the continuous phase and a 'water drops in oil' regime was noted. At a lower superficial oil velocity a transition to 'oil in water concentric' flow was observed followed by the flow patterns 'oil slugs in water', 'oil bubbles in water' and 'oil drops in water' in which water was the continuous phase. The flow patterns for the least viscous oils were similar; the patterns for the most viscous oil were similar to those of the least viscous oils at high superficial water velocities, but at low superficial water velocities and high oil-water input ratios a dissimilarity occurred in

that for the most viscous oil, a series of flow patterns was obtained with oil as the continuous phase.

Pressure drop and holdup data were noted for the three oils at various superficial oil velocities for superficial water velocities of 0.1, 0.3, 0.8, 1.8 and 3.5 ft. per sec. The pressure drop data are presented as modified friction factors based on the water properties. At low oil-water input ratios the modified friction factors were largely independent of the oil viscosity but at high input ratios much higher friction factors were obtained for the more viscous oil when this oil formed the continuous phase and was in contact with the pipe wall.

For a given superficial water velocity the holdup ratio was a maximum for the 'oil in water concentric' flow pattern. This indicates a relatively high accumulation of water in the pipe for this flow system. At low input oil-water ratios the holdup ratio was found to be largely independent of the superficial water velocity.

# INTRODUCTION

A knowledge of the factors affecting the simultaneous movement of crude oil and water in pipelines is important in the petroleum transportation industry. Water is often produced in large quantities with crude oil and although most of the water is usually separated from the crude oil under the influence of gravity at the wellhead storage tanks, the separation is not complete, particularly in the case of heavy viscous oils. The oil with the entrained water is then usually transferred by pipeline to the oil treating and refining facilities. When the amount of water produced with the oil is low wellhead separation equipment may not be justified and again the water is moved by pipeline with the oil.

For many years the beneficial effect which accrues from the introduction of water in controlled amounts into pipelines carrying heavy viscous crude oil has been recognized. The introduction of water can reduce the pressure gradient along the pipeline and the power requirement necessary to pump a given quantity of oil. Further practical knowledge and a proper scientific understanding of this phenomenon would be advantageous.

In general two immiscible liquids have different densities and there is a tendency for them to stratify when flowing together in a pipeline. The greater the density differential the more complete is the stratification. In the case of oil and water, the oil usually has a density less than that of the water and forms an upper layer flowing

above the water. Stratified flow has been investigated by Russell, Hodgson and Govier (7) in a horizontal pipeline of one inch diameter. Pressure gradient data and holdup measurements were obtained for a white mineral oil of specific gravity 0.834 and viscosity 22 cp. at 20° C. The pressure drop data were plotted as a modified Fanning friction factor based on water properties versus a superficial water velocity. Three flow patterns were observed which were designated bubble flow, stratified flow, and mixed flow. Holdup measurements indicated that in the laminar region of flow the holdup ratio was a function of the liquid input ratio and the viscosity whilst in the turbulent region the holdup ratio was also a function of the superficial water velocity.

Sullivan et al (8) investigated the upwards vertical flow of two phases (a reference phase of water and a second phase of air or oil) in pipe diameters of 1.5 inches and 1.025 inches. The pressure drop data were presented as a friction factor plotted in terms of the superficial velocities of the two phases, pipe diameter and difference in kinematic viscosity of the phases. The holdup ratio was correlated with the velocities of the two phases, the densities of the phases and the pipe diameter. Although a density differential existed stratification did not result because the flow was vertical.

Mention has been made of the possibility of reducing crude oil pipeline pressure drops by the addition of water. The flow system which apparently is most

attractive from the viewpoint of pressure drop reduction is the concentric flow of oil and water. In this system the less viscous water forms a uniform film in the region of high shear rate next to the pipe wall. Russell and Charles (6) in a paper on the theoretical aspect of the problem analysed laminar stratified liquid flow between wide parallel plates and concentric laminar flow of two liquids with the same densities but different viscosities in a circular pipe. For the concentric flow system equations were presented for the flow rates of the two liquids, the pressure gradient and the power requirement. The optimum factor by which the pressure gradient can be reduced was shown to be proportional to the viscosity of the oil when the oil viscosity is very much greater than the viscosity of the water. It was stated, however, that although the possible power savings are very large the concentric flow system would be difficult to maintain in practice where a density differential would tend to produce stratification.

Patents by Clark and Shapiro (3) and Chilton and Handley (2) deal with the commercial application of water to reduce oil pipeline pressure gradients. Both indicated that the water should flow as a film on the pipe wall but acknowledged the difficulty introduced by a density differential. Clark and Shapiro suggested that 8-10% water provided an optimum pressure gradient reduction whilst Chilton and Handley suggested that 1% would be more suited to commercial operation and indicated a

method by which the water could be introduced through a set of holes spaced equally around the pipe wall.

The concentric flow system was also considered by Yuster.(9) He was concerned with the relative permeability of oil and water in porous media and derived flow rate equations, which were similar to those developed by Russell and Charles, for concentric flow in an idealised capillary system.

Heavy crude oils have densities which approach the density of water and it was thought that much useful information could be obtained by an investigation into the flow characteristics of the idealised system in which the oil and water have the same density.

## THEORY

The relationship between pressure gradient and fluid flow rate for a single liquid flowing in a circular pipe is usually represented by the friction factor-Reynolds number plot where the Fanning friction factor is defined as:

$$f = \frac{\Delta P d g_c}{2 \Delta L \rho V^2} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $\frac{\Delta P}{\Delta L}$ = pressure gradient, $lb_f$. per $ft.^2$ per ft.

$d$ = pipeline diameter, ft.

$V$ = average fluid velocity, ft. per sec.

$g_c$ = dimensional conversion factor, $lb_m$. ft. per $lb_f$.sec.

$\rho$ = fluid density, $lb_m$. per $ft.^3$

and Reynolds number is defined as:

$$Re = \frac{Vd\rho}{\mu} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $\mu$ = dynamic fluid viscosity, $lb_m$. per ft. sec.

The simultaneous flow of two fluids is more complex and the friction factor and Reynolds number defined above cannot be used without modification. Russell et al (7) used the superficial water velocity instead of the Reynolds number and a modified friction factor based on the water properties. This convention will be adopted in the present study. A friction factor is defined as:

$$f_w = \frac{\Delta P d g_c}{2 \Delta L \rho_w V_w^2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $f_w$ = a friction factor based on the water properties

$\rho_w$ = density of water, $lb_m$. per $ft.^3$

$V_w$ = superficial water velocity, ft. per sec.

The superficial water velocity is the velocity the water would have if it alone occupied the pipe and is simply obtained by dividing the water flow rate ($ft.^3$ per sec.) by the pipe cross sectional area ($ft.^2$)

In two phase flow the relative flow rates of the two fluids is important and the input ratio, $R_v$, is defined as:

$$R_v = \frac{Q_o}{Q_w} = \frac{V_o}{V_w}$$

where $Q_o$ = volumetric flow rate of oil, $ft.^3$ per sec.

$Q_w$ = volumetric flow rate of water, $ft.^3$ per sec.

$V_o$ = superficial oil velocity, ft. per sec.

Since the densities of the oil and water phases are identical in this study the input ratio is also equal to the ratio of the mass rates of flow.

The holdup ratio, $H_R$, is defined as the ratio of the input oil-water ratio to the in situ oil-water ratio.

$$\text{i.e.} \quad H_R = \frac{R_v}{\text{in situ ratio}}$$

In general, the holdup ratio differs from unity because the liquid in contact with the pipe wall tends to be held back in the pipe. The holdup ratio for the concentric flow system can be derived theoretically from the

flow rate equations* of Russell and Charles (6), which are:

$$Q_o = \frac{\pi r_i^4 g_c}{8} \left(\frac{\Delta P}{\Delta L}\right)\left[\frac{1}{\mu_o} + \frac{2}{\mu_w}\left(\frac{R^2}{r_i^2} - 1\right)\right] \quad . \quad (4)$$

and $$Q_w = \frac{\pi g_c}{8\mu_w}\left(\frac{\Delta P}{\Delta L}\right)\left[R^2 - r_i^2\right]^2 \quad . \quad . \quad . \quad (5)$$

where $\mu_o$ = viscosity of oil, $lb_m$. per ft. sec.

$\mu_w$ = viscosity of water, lb. per ft. sec.

$r_i$ = radius of oil-water interface, ft.

$R$ = radius of pipe, ft.

For concentric flow the in situ oil-water ratio:

$$= \frac{r_i^2}{R^2 - r_i^2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and hence the holdup ratio, $H_R$,

$$= \frac{Q_o/Q_w}{r_i^2/R^2 - r_i^2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Substitution of equations (4) and (5) in equation (7) gives after simplification:

$$H_R = 2.00 + \frac{\mu_w}{\mu_o}\,\frac{r_i^2}{R^2 - r_i^2} \quad . \quad . \quad . \quad (8)$$

or $$H_R = 2.00 + \frac{\mu_w}{\mu_o} \text{ (in situ ratio)} \quad . \quad . \quad (9)$$

Equation (9) indicates that, for laminar concentric flow the holdup ratio is always greater than 2.00 but approaches 2.00 when the viscosity ratio, $\frac{\mu_w}{\mu_o}$, or the in situ ratio is very small.

* it is assumed in these equations that the water is in contact with the pipe wall

## EXPERIMENTAL EQUIPMENT

The pipeline used in the present work, together with the subsidiary items of equipment and piping connections, is shown schematically in Figure 1. Photographs of the pipeline are presented in Plates 1 to 5. Satisfactory pipeline operation was achieved with oil and water storage facilities, pipeline test section, oil and water separation equipment, a salt tower to dehydrate the recycled oil, and a combined heater-cooler for the oil.

Control and measurement of the variables were obtained with rotameters for the oil and water flow rates, differential water and mercury manometers for the pipeline pressure drop, and simple volume measuring equipment for the in situ contents of the pipeline.

In order to carry out the tests three oils were required with viscosities in the range 5 to 100 cp. but each with a density of 0.998 gm. per $cm.^3$ - the density of water at the flowing temperature of 25° C. Commercially refined oils were available in the correct viscosity range but their densities were in the range 0.8 - 0.9 gm. per $cm.^3$ Consequently it was necessary to add a second liquid with a density greater than that of water to give the required oil densities of 0.998 at 25° C. Carbon tetrachloride with a specific gravity of 1.59 was selected on the basis of high density and reasonably low cost as the most suitable liquid for the purpose. Other chlorinated organic solvents could have been used but these were generally

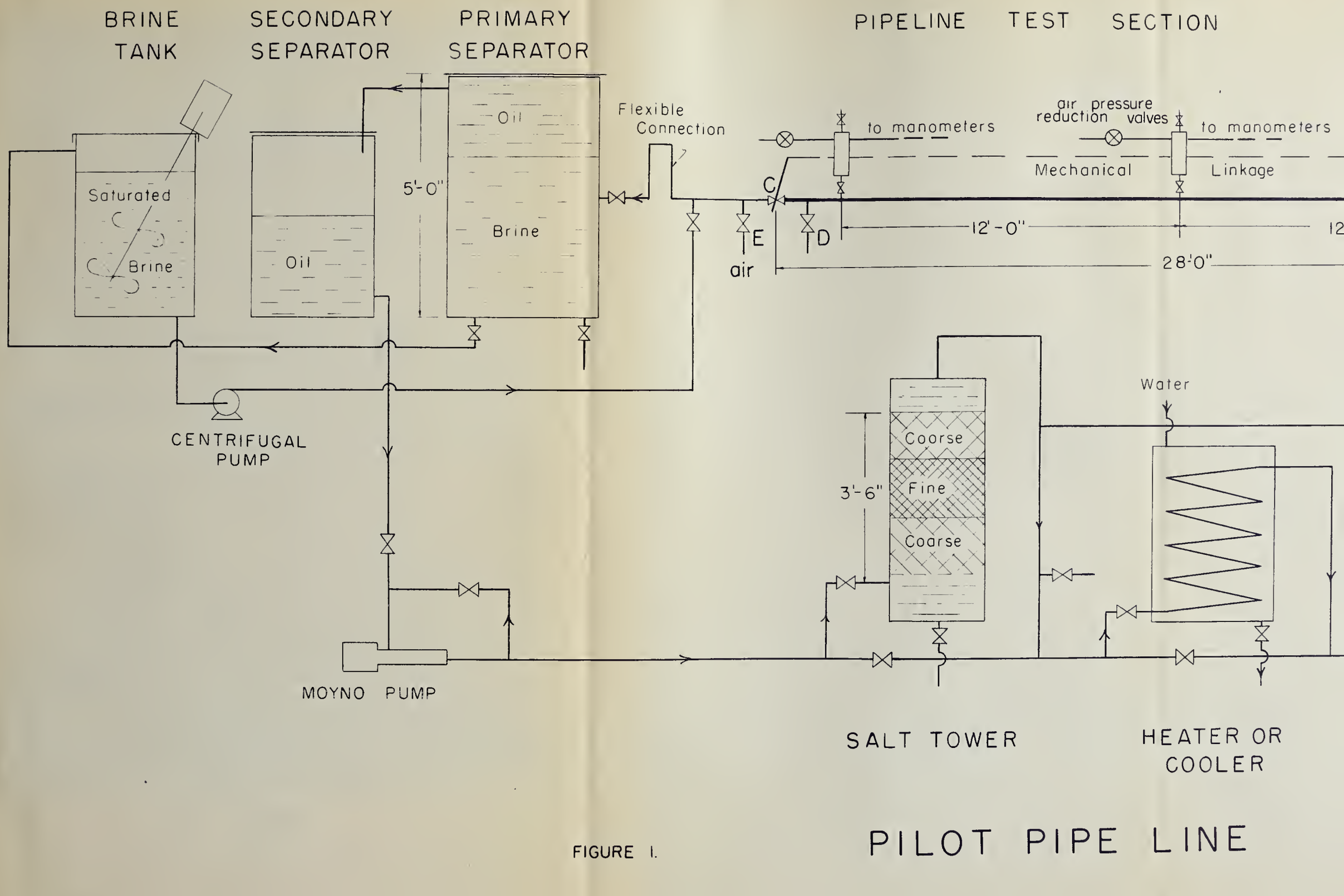
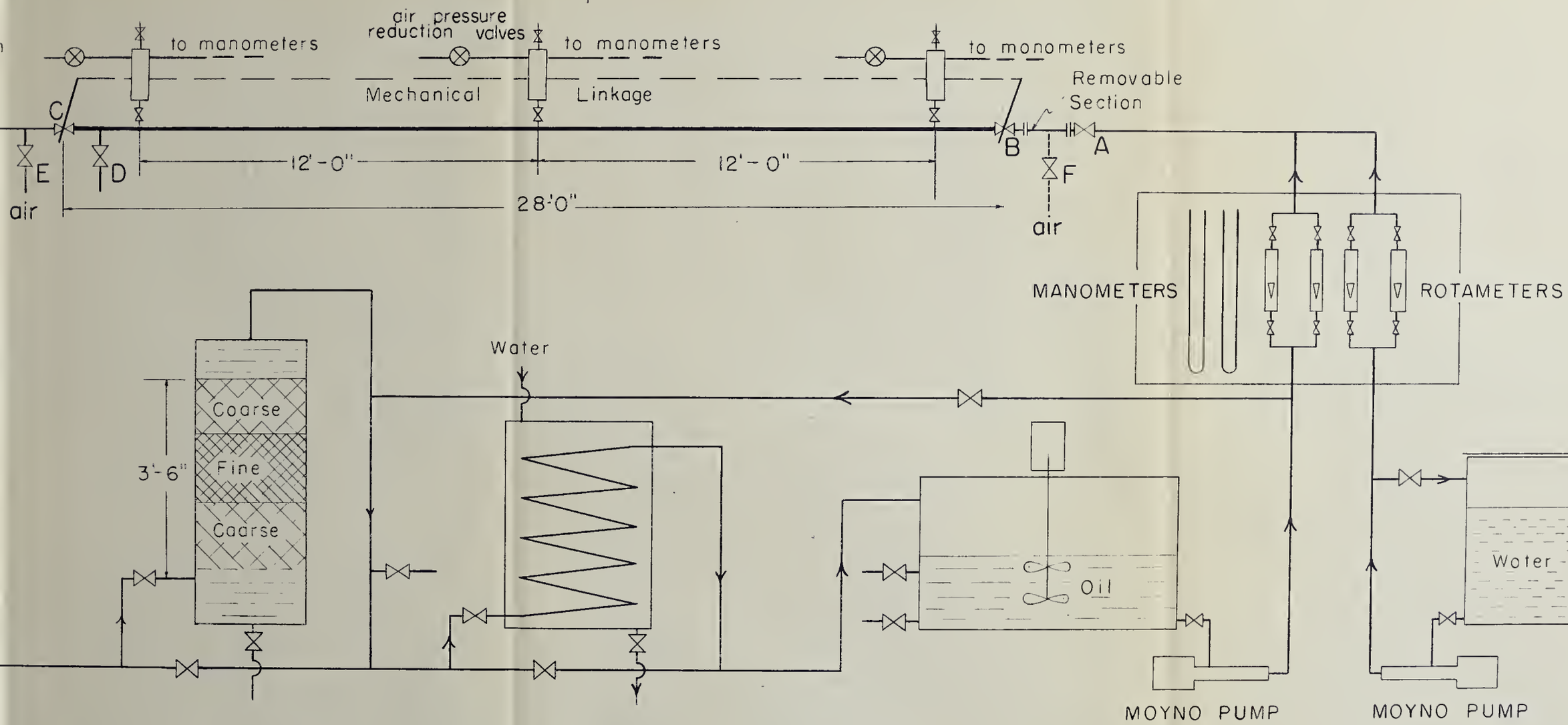



FIGURE 1.

# PILOT PIPE LINE

PIPELINE TEST SECTION

CONTROL PANEL




SALT TOWER

HEATER OR COOLER

OIL STORAGE

WATER STORAGE

# PILOT PIPE LINE

NOT TO SCALE



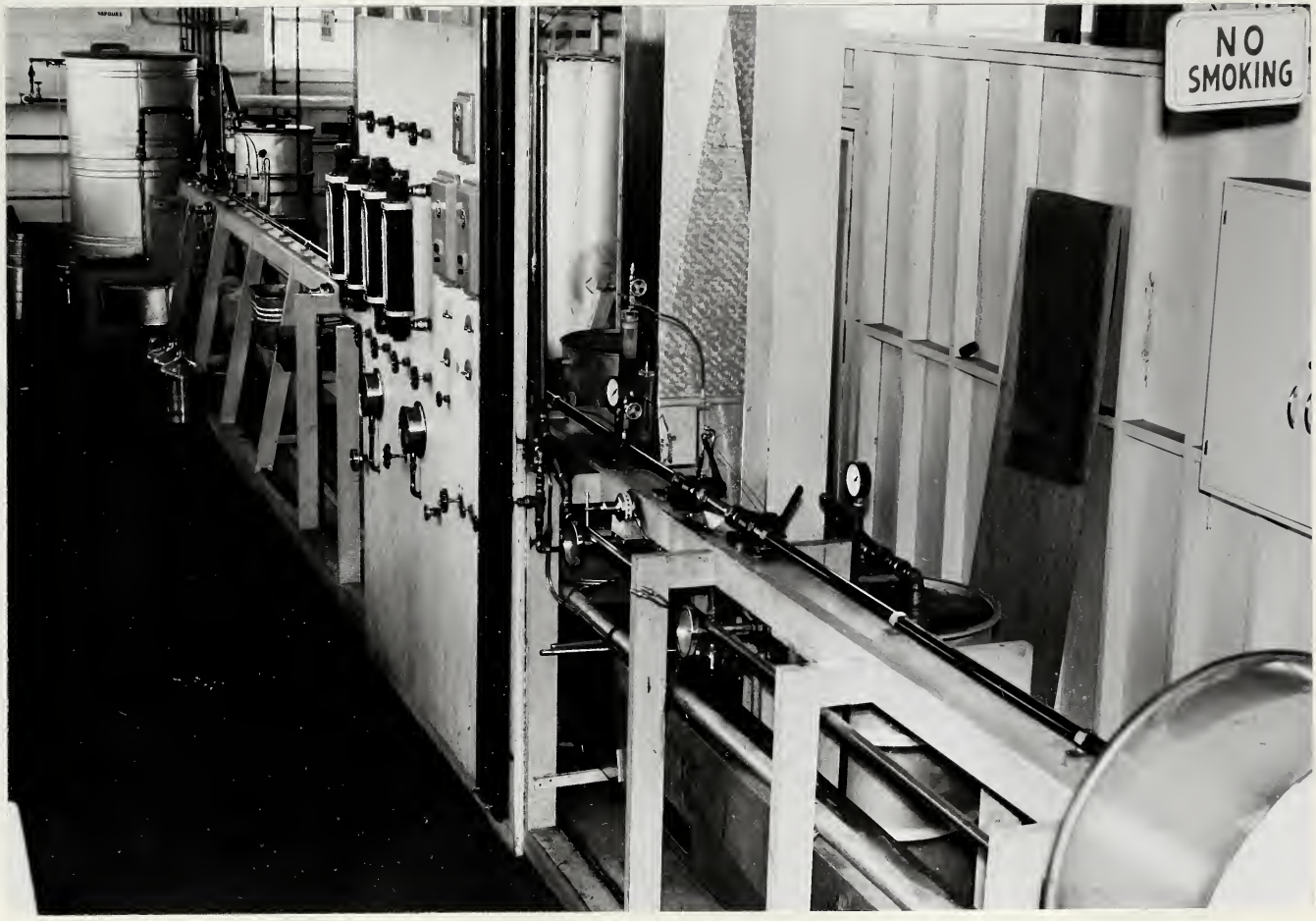



PLATE 1. OVERALL VIEW OF PIPELINE



PLATE 2. SALT TOWER, WATER STORAGE TANK, CONTROL PANEL AND OIL AND CARBON TETRACHLORIDE SUPPLY DRUMS ABOVE THE OIL STORAGE TANK.

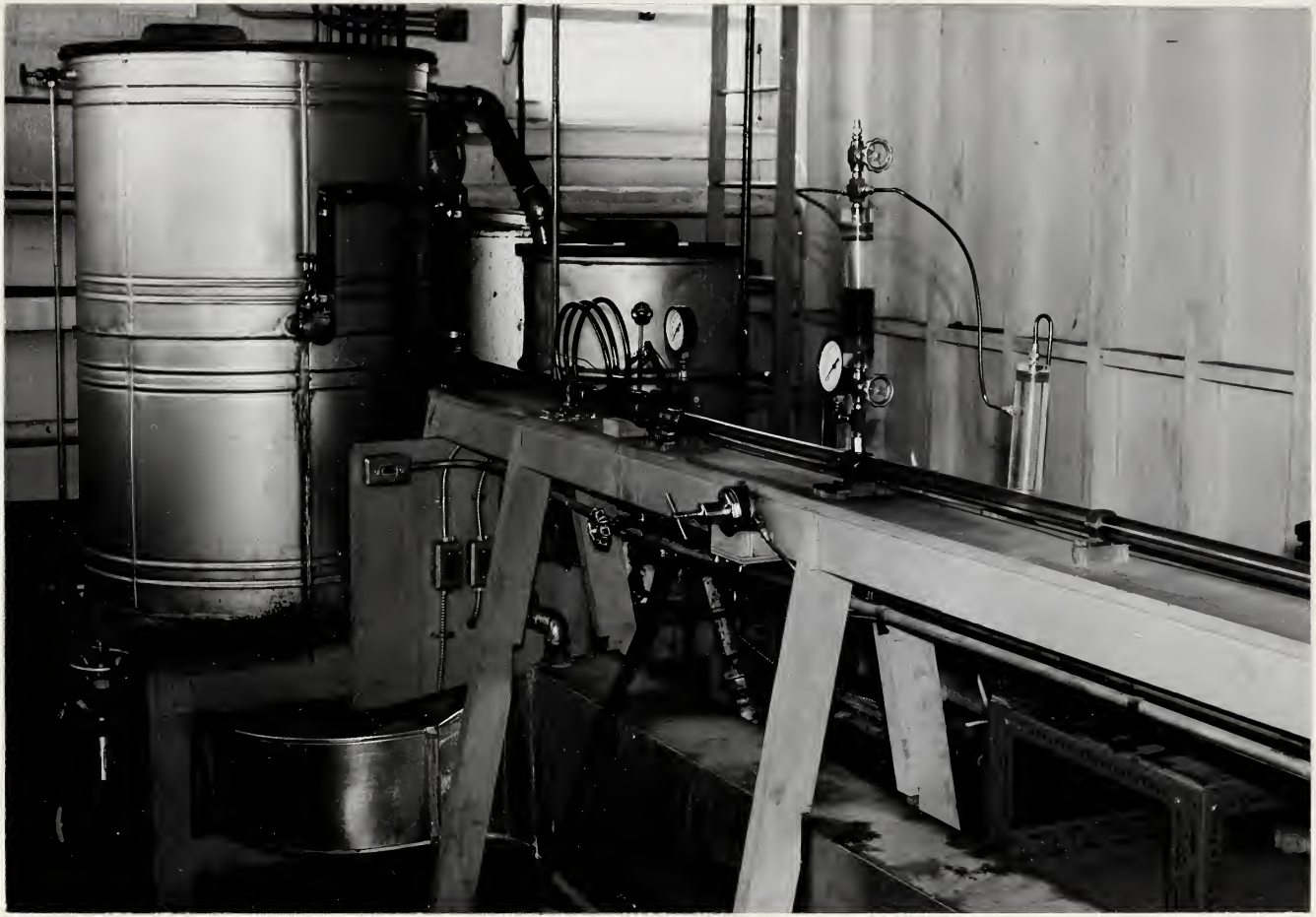


PLATE 3. OIL AND WATER SEPARATION UNIT.

The primary separator with the secondary separator and brine tank.

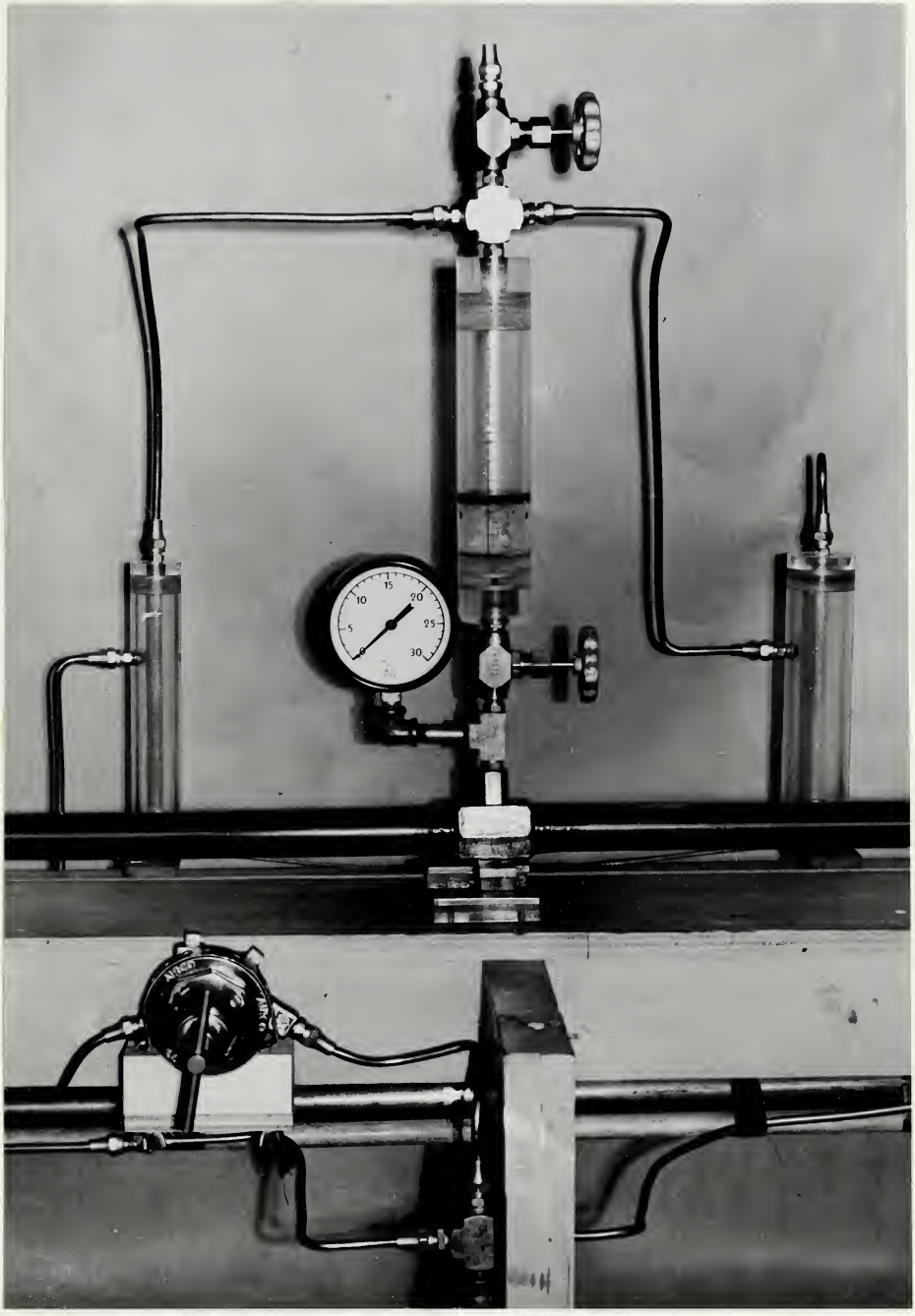



PLATE 4. PRESSURE MEASURING STATION.

Splashpot, with pressure gauge and catchpots, mounted on brass slide. Also air pressure reduction valve.

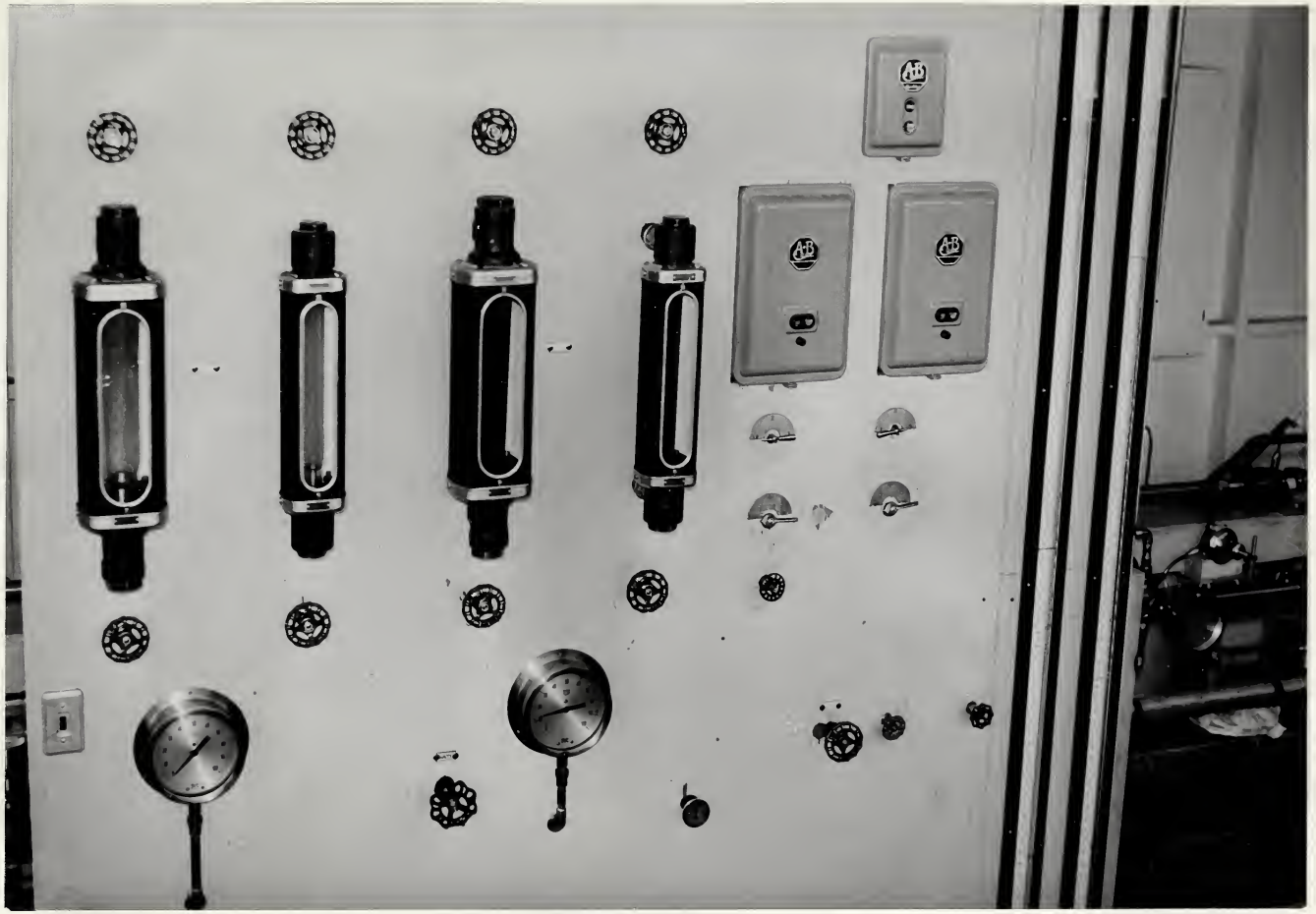


PLATE 5. PIPELINE CONTROL PANEL

less dense and much more expensive than carbon tetrachloride.

However, the inhalation of carbon tetrachloride is a serious toxic hazard unless adequate precautions are taken in ventilation and in the confinement of vapour. Consequently the pipeline area was provided with its own exhaust system and care was taken to eliminate possible points of loss of carbon tetrachloride to the atmosphere. Care, in this respect, was particularly necessary during the measurement of the in situ contents of the pipeline.

Three commercially refined oils Marcol GX, Wyrol J and Teresso 85, all supplied by Imperial Oil Ltd., were used as the bases for the three test oils. The test oil with a viscosity of 6.29 cp. at 25°C. was a mixture of Marcol GX and carbon tetrachloride; the test oil with a viscosity of 16.8 cp. at 25°C. was a mixture of Wyrol J and carbon tetrachloride and the test oil with a viscosity of 65.0 cp. at 25°C. was a mixture of Teresso 85 and carbon tetrachloride. The properties of the commercial oils are given in Table 1 and of the test oils in Table 2.

| | Oil Type | Viscosity cp. at 25°C. | Density $gm/cm^3$ at 25°C. | Colour |
|---|---|---|---|---|
| Marcol GX | White mineral oil | 17.5 | 0.853 | clear |
| Wyrol J | White mineral oil | 67.0 | 0.878 | clear |
| Teresso 85 | Lubricating oil containing anti-corrosion compounds | 412 | 0.893 | light amber |

TABLE 1. COMMERCIAL OIL PROPERTIES

| Viscosity cp. at 25°C. | Density gm/cm.$^3$ at 25°C. | Approximate CCl4 content (volume%) | Colour |
|---|---|---|---|
| 6.29 | 0.998 | 26 | clear |
| 16.8 | 0.998 | 23 | clear |
| 65.0 | 0.998 | 20 | *dark green-brown |

TABLE 2. TEST OIL PROPERTIES

The pipeline equipment is now considered in detail.

Oil and Water Storage Facilities

The test oil supply was contained in a 250 U.S. gallon tank containing a double propeller-type mixer driven by a 0.25 horse power electric motor. Two 45 U.S. gallon drums containing the commercial oil and carbon tetrachloride, although not shown in Figure 1, were mounted above the test oil storage tank and pure oil or carbon tetrachloride was gravity fed as required to maintain the density of the test oil. The temperature of the oil was indicated by two bimetallic gauge thermometers fitted into the recycle line. The water supply was contained in a 45 U.S. gallon tank fitted with two bimetallic gauge thermometers.

Screw-type positive displacement Moyno pumps (model 214-CDQ, manufactured by Robins and Meyer) driven by 7.5 horse power electric motors and with capacities of 2.02 U.S. gallons per 100 RPM delivered the oil and water separately to the Fischer Porter rotameters. The flows

* colour appeared on exposure to light.

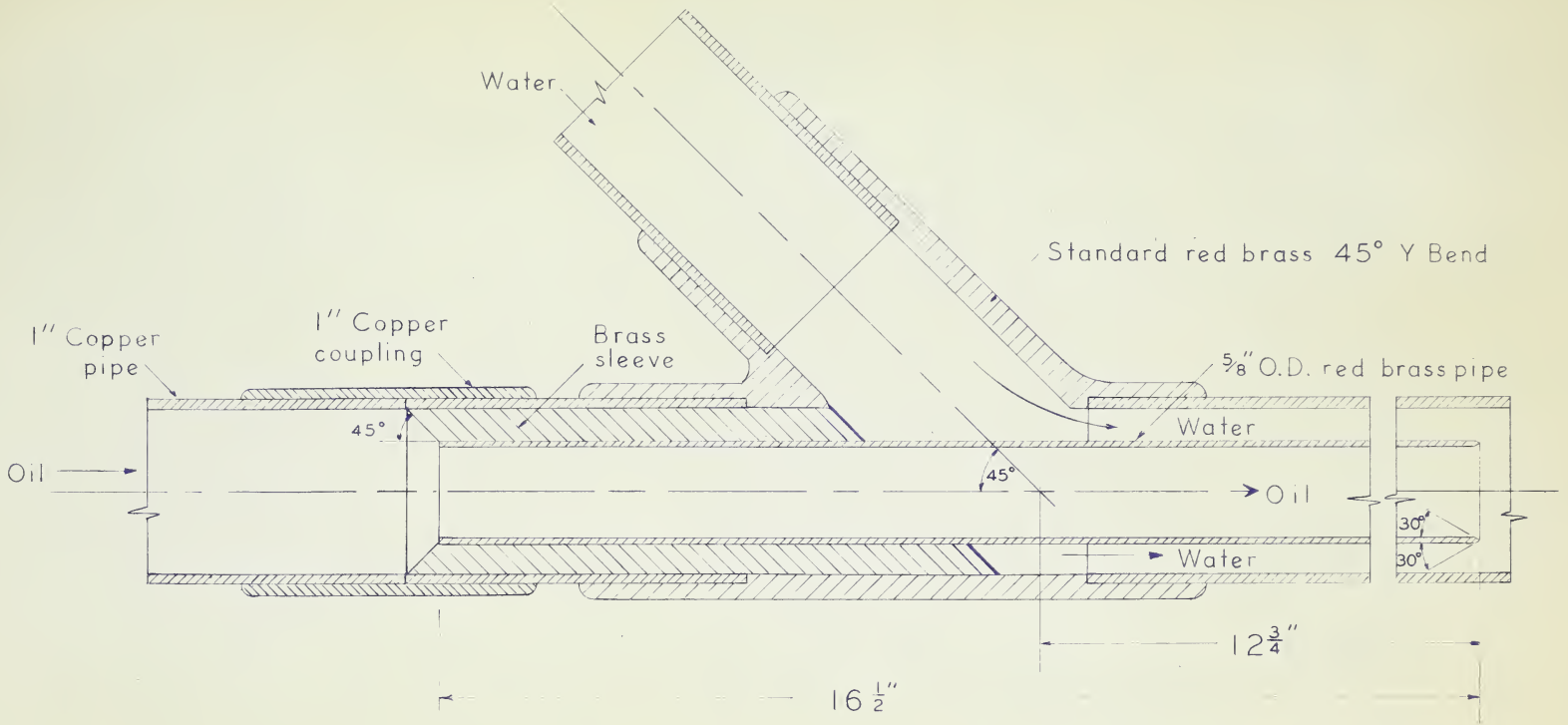
through the rotameters and hence through the pipeline test section were controlled by operating by-pass valves on the pumps and valves on each side of the rotameters. Spring loaded cut-out switches were installed in the discharges of both pumps as a safety measure. These switches automatically switched the pumps off if the pressure rose above 40 lb./in.$^2$ gauge.

The metered oil and water flows were combined concentrically at the beginning of a 10 ft. long calming section by means of a nozzle where the oil was introduced inside the water annulus. A diagram of the nozzle is given in Figure 2.

Govier, Radford and Dunn (4) when concerned with two-phase air-water flow concluded that the mechanical design of the injection nozzle did not affect the flow pattern and used a simple tee in their work. Hence it was assumed that the form of the nozzle would not influence the flow pattern in this study. However, since another project for which the pipeline was designed was the detailed study of the "oil in water concentric" flow regime, a nozzle was designed which appeared to give encouragement to the establishment of the concentric system.

Pipeline Test Section

The pipeline was supported in a horizontal position by a wooden trestle constructed mainly from 2 in. x 4 in. timbers. The test section consisted of 28 ft. of 1.04 in. I.D. clear butyrate pipe (Busada 210, supplied by




# OIL AND WATER FEED SYSTEM TO PIPELINE.

SCALE: FULL SIZE

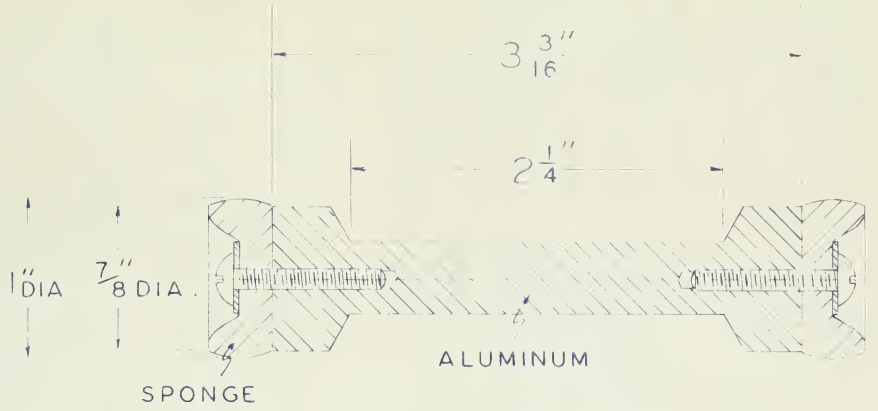
FIGURE 2

the Busada Supply Co. Inc.) with an approach calming section 10 ft. long.

The possibility was forseen that the flow pattern would not become steady over the calming section and the pipeline was designed with three pressure tappings so that the pressure drop over the first and second halves of the test section could be compared. The tappings were drilled through brass couplings 12 ft. apart. However, the flow patterns were visually observed to become steady within the calming section. Consequently, throughout the tests, only the tappings at the ends of the test section were used.

At the ends of the test section were 1 in. A.C.F. ball valves, the operating arms of which were joined by a taut steel cable. This cable enabled the valves to be closed simultaneously in the measurement of the in situ contents of the pipeline test section.

The measurement of the in situ contents necessitated a method of ejecting the liquids from the pipeline and into volume measuring equipment. The passage tnrough the pipeline of a 'pig', which closely fitted the internal surface of the line, provided a fast, efficient method. A diagram of the 'pig' is presented in Figure 3. The 'pig' was introduced into the pipeline at a removable brass section, which was 8 in. long and situated immediately upstream of the test section. Two such brass sections, which were identical except that one had a flexible air line attached, were manufactured. The section without the air




SECTION THROUGH 'PIG'

FIGURE 3

line was in place during pressure drop measurement and this section was fitted with union couplings which were machined on the inside surfaces to give a smooth passage to the flowing liquids. After the pressure drop had been recorded and the flow stopped the second section containing the 'pig' was substituted into the pipeline and the 'pig' pushed through the test section under air pressure.

A third ball valve was located upstream of the removable brass section. This valve was closed during the measurement of the in situ contents of the pipeline test section to prevent oil and water flowing from the pipeline when the short brass section was removed.

The pipeline was mounted on brass slides, one of which is shown in Plate 3, so that, with a flexible coupling between the pipeline and the separation unit, the pipeline was free to expand and contract under the influence of ambient temperature.

Separation Unit

Economy necessitated the separation of the oil from the water and its return to the test oil storage tank. The oil and water separation unit consisted of a 200 U.S. gallon primary separator, a 45 U.S. gallon secondary separator, a 65 U.S. gallon brine tank and a salt tower.

When a sufficient density differential exists, liquids separate readily under the influence of gravity. In order that gravity separation could be used to separate the oil and water a saturated brine(sodium chloride)

solution was injected by a centrifugal pump into the liquids leaving the pipeline test section. The brine increased the density of the aqueous phase and two liquid layers formed in the primary separator, the more dense diluted brine forming the lower layer. Some of this brine was recycled to the brine tank and the excess was run to waste; when the lower layer was diluted to such an extent that the density fell below about 1.10 gm. per $cm^3$ the lower layer was run to waste and replaced by a saturated brine solution with a density of 1.206 gm. per $cm^3$.

The upper oil layer, which usually contained a small amount of water dispersed as small droplets, was transferred to the secondary separator. A Moyno pump taking suction on the secondary separator transferred the oil through the salt tower to the test oil storage tank.

The salt tower was necessary to remove the last traces of water from the oil. The tower was six feet high and fourteen inches in diameter and the position of the point of introduction of the oil was about one foot from the bottom. The salt bed weighed approximately five hundred pounds and consisted of two layers of coarse salt separated by a layer of fine salt and supported on a wire gauze lying on a strong grid. The tower was flanged at the top and at the bottom to facilitate the removal of spent salt. The clean oil left at the top of the tower. The average oil throughput for the salt tower before it became necessary to replace the salt bed was estimated to be about 500 U.S. gallons.

Temperature Control Equipment

The desired flowing temperature of both the oil and water was 25°C. The temperature of the oil was controlled by a simple unit in which the oil flowed through four 5/8 in. copper coils 25 ft. long surrounded by hot or cold water. The oil was recycled until the desired temperature was registered at the inlet to the unit.

The water temperature was controlled by adjusting the relative flows of hot and cold water into the storage tank.

Control and measurement of the variables were obtained with the aid of rotameters for the oil and water flow rates, differential water and mercury manometers for the pipeline pressure drop, and simple volume measuring equipment for the in situ contents of the pipeline.

Flow Meters

Large and small rotameters in parallel, all with interchangeable steel and plastic floats were used to meter both the oil and water flows. The large and small rotameters had capacities of approximately 21 and 5.7 U.S. gallons per min. and the minimum capacities of approximately 1.5 and 0.3 gallons per min. respectively.

Pressure Drop Manometers

The differential pressure between any two of the tappings on the pipeline test section could be registered on

either a water or mercury manometer. The method used for transmitting the pressures was similar to that by Russell et al (7). Mounted above the pipeline at the pressure tappings were splash pots, one of which is shown in Plate 3. Air was supplied to the splash pots through pressure reduction valves. Each splash pot was fitted with a pressure gauge, a vent, a needle valve in the connection to the pipeline and an air line to the manometer system. Catchpots in the air lines to and from a splash pot prevented oil or water being accidentally entrained in the air pressure reduction valves or manometer lines. Marks on each splash pot enabled the liquid to be adjusted to the same absolute level in each splash pot.

Holdup Measurements

The calculation of the holdup ratio necessitated a knowledge of the in situ contents of the pipeline. The 'pig' shown in Figure 3 was used to eject the liquids contained in the pipeline and the volumes of oil and water were measured in graduated cylinders.

## EXPERIMENTAL PROCEDURE

A description of the rotameter calibration and the calibration curves are presented in Appendix A.

The pressure measuring equipment and rotameter calibrations were checked by taking pressure drop measurements for various flow rates of water and the test oils alone and comparing the resulting plot of the calculated friction factors against Reynolds number with the accepted curves. This comparison is presented in Figure A 4 of Appendix A.

Experiments were made to study the flow of the three test oils in the presence of water over a range of superficial oil velocity from 0.05 ft. per sec. to 3.0 ft. per sec. and a range of superficial water velocity from 0.1 ft. per sec. to 3.5 ft. per sec. For given flow rates of oil and water the flow pattern was noted, and the pressure drop between the extreme stations on the test section and the in situ contents of the pipeline were measured.

An experiment is now described in detail. Flows of hot and cold water into the water storage tank were adjusted to give the required water temperature of 25°C. The temperature of the oil was raised by recycling the oil through the heater. When the oil temperature reached 25°C. the oil was caused to bypass the heater and the density of the oil was checked using a hydrometer in a sample taken from the storage tank. Invariably the density was low(for example 0.995 gm. per $cm^3$ compared with the required value

of 0.998 gm. per $cm.^3$) because of the loss of carbon tetrachloride vapour. Carbon tetrachloride was added to produce the required density whilst the propeller mixer and the action of recycling produced adequate mixing and a uniform oil supply.

All valves between the oil and water pumps and the primary separator were opened and the brine pump started. The oil and water pumps were started and flow was allowed through all rotameters until all air entrained in the lines was removed. Bypass valves and valves on each side of the rotameters were adjusted to give the required flow rates of oil and water. Visual observation indicated when steady conditions had been obtained and a note was made of the flow pattern. The period of time necessary to establish steady conditions was usually one to several minutes and depended on the flow rates. In general, the slower the flow rate the longer the time required to obtain steady conditions.

To obtain pressure drop measurements the extreme pressure tappings were opened and the liquid levels in the splashpots adjusted to the same absolute level. Air pressure was used to balance the line pressure. The splash pots were then opened to the manometer system and a final adjustment made to the liquid levels in the splashpots. The pressure differential as registered by the water or mercury manometer was then recorded.

After the measurement of pressure drop the in situ oil-water ratio was measured as follows. The pressure tappings were closed and after checking the rotameters to

ascertain that the correct flow rates were being maintained the quick action valves, B and C (see Figure 1) were closed and the oil and water pumps stopped simultaneously. Valve A was closed and the section of pipe between valves A and B was removed, care being taken to confine the liquid content of the section in a small sump beneath the pipeline. This section was replaced by the similar section which contained the 'pig' and had the flexible air line attached.

The drain valve D, the valve B and the air valve F were opened and contents of the pipeline discharged into a container containing 2000 ml. of concentrated brine solution. The 'pig' was removed from the line at the same point as it was inserted by closing valves F and D and opening valve C and the air valve E. The original section between valves A and B was then replaced.

After vigorous manual shaking the contents of the pipeline and the brine were allowed to settle and subsequently the volumes of oil and water were measured in graduated cylinders. The in situ contents of the pipeline were thus determined and the in situ ratio calculated.

Sets of measurements were made in this way, with periodic checks on the oil and water temperature until all the oil had been used. Sufficient time was allowed for the oil to become substantially water-free and the level of the oil-brine interface in the primary separator was raised by the addition of brine. The oil was thus transferred to the secondary separator, from where the Moyno pump returned it through the salt tower to the storage tank.

## EXPERIMENTAL RESULTS AND DISCUSSION

Pressure drops were recorded for water and the three test oils flowing alone. The calculated friction factors and Reynolds numbers are plotted in Figure A4 of Appendix A. The data show good agreement with the theoretical curve in the laminar region and with the Blasius equation in the turbulent region and it is assumed from this that the calibration of the rotameters and the pressure drop measuring system were accurate.

Flow patterns were noted for the flow of water with each of the test oils over a range of superficial water velocity from 0.1 to 3.5 ft. per sec. and a range of superficial oil velocity from 0.05 to 3.0 ft. per sec. Examples of the flow patterns are presented in Plates 6, 7 and 8 and the flow regimes are indicated in Figures 4 and 5.

Pressure drops and in situ oil-water ratios were measured for various superficial oil velocities at superficial water velocities of 0.1, 0.3, 0.8, 1.8 and 3.5 ft. per sec. Modified friction factors based on the water properties were calculated from the pressure drops and are shown plotted against the input oil-water ratio in Figures 7, 8 and 9, and against superficial water velocity in Figures 10, 11 and 12.

Holdup ratios calculated from the input and in situ oil-water ratios are plotted against the input oil-water ratio in Figures 13, 14 and 15.

Flow patterns

Photographs of representative flow patterns were taken for the 16.8 cp. oil and are presented in Plates 6, 7 and 8. The three plates of photographs show the effect on the flow pattern of the oil flow rate at constant superficial water velocities of 0.1 ft. per sec. (Plate 6), 0.682 ft. per sec. (Plate 7) and 2.04 ft. per sec. (Plate 8).

The flow pattern obtained with high superficial oil velocities at a superficial water velocity of 0.1 ft. per sec. is shown in Photographs 1 and 2 in Plate 6 where the superficial oil velocities are 2.27 and 1.36 ft. per sec. respectively. The water is dispersed as small droplets in a continuous phase of oil and this flow pattern is designated 'water drops in oil'.

Reduction in the superficial oil velocity to about 1.2 ft. per sec. caused both oil and water to be present as continuous phases. Concentric flow, in which the oil formed a continuous core along the axis of the pipe and the water a uniform layer on the pipewall, is shown in Photograph 3 for a superficial oil velocity of 0.454 ft. per sec.This flow pattern is designated 'oil in water concentric'.

A further reduction in superficial oil velocity at a superficial water velocity of 0.1 ft. per sec. resulted in the oil phase becoming discontinuous. The oil flowed as slugs and, at lower superficial oil velocities, as bubbles. The 'oil slugs in water' flow pattern is shown

for a superficial oil velocity of 0.200 ft. per sec. in Photograph 4 and the 'oil bubbles in water' flow pattern is shown for a superficial oil velocity of 0.050 ft. per sec. in Photograph 5. The small water bubbles entrained in the oil slugs in Photograph 4 were due to a temporary roughness in the pipe and are not characteristic of the flow pattern.

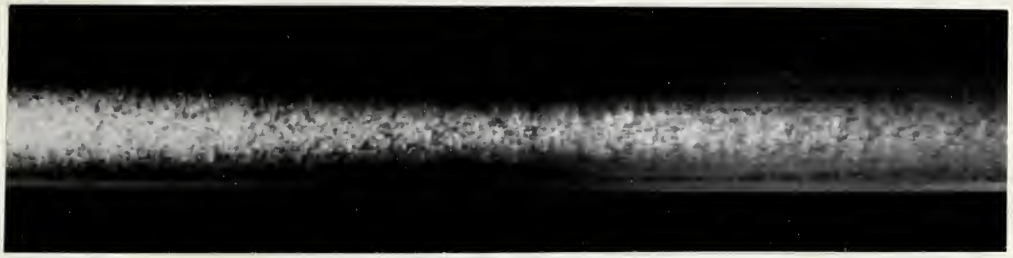
The effect on the flow pattern of reducing the superficial oil velocity at a superficial water velocity of 0.682 ft. per sec. is shown in Photographs 6 to 9 in Plate 7. At high superficial oil velocities the water was dispersed as small droplets, and an example of the 'water drops in oil' flow pattern is shown in Photograph 6 for a superficial oil velocity of 1.95 ft. per sec. Reduction in superficial oil velocity again resulted in 'oil in water concentric' flow and an example is shown for a superficial oil velocity of 1.11 ft. per sec. The flow pattern is more disturbed compared with the concentric flow at a superficial water velocity of 0.1 ft. per sec. The photograph shows that the oil-water interface is wavy and that some water is entrained in the oil.

A further reduction in superficial oil velocity again resulted in 'oil slugs in water' flow and subsequently 'oil bubbles in water' flow. An example of slug flow is shown in Photograph 8 for a superficial oil velocity of 0.682 ft. per sec. and an example of bubble flow is shown in Photograph 9 for a superficial oil velocity of 0.200 ft. per sec.

The effect on the flow pattern of reducing the superficial oil velocity at a superficial water velocity of 2.04 ft. per sec. is shown in Photographs 10 to 12 in Plate 8. At high superficial oil velocities the 'water drops in oil' flow pattern was again encountered. At a lower superficial oil velocity of 1.82 ft. per sec. the very disturbed form of 'concentric' flow shown in Photograph 10 was noted and a further reduction in superficial oil velocity gave the 'oil slugs in water', the 'oil bubbles in water' and the 'oil drops in water' flow patterns. At this superficial water velocity of 2.04 ft. per sec. it was difficult to differentiate between the slug, bubble and drop flows because for a given superficial oil velocity the oil was present as slugs, bubbles and drops of various sizes. An example, which is considered to be intermediate between slug and bubble flow is shown in Photograph 11 for a superficial oil velocity of 0.682 ft. per sec. 'Oil drops in water' flow is shown for a superficial oil velocity of 0.200 ft. per sec. in Photograph 12.

The photographs indicate that for the 'oil in water concentric', 'oil slugs in water', 'oil bubbles in water' and 'oil drops in water' flow patterns the pipe was always in a water wet condition.

The flow pattern regimes are shown for the 6.29 and the 16.8 cp. viscosity oils in Figure 4 and for the 65.0 cp. viscosity oil in Figure 5 where the superficial oil and water velocities are represented on logarithmic



1

$V_o$ = 2.27 ft. per sec.



2

$V_o$ = 1.36 ft. per sec.



3

$V_o$ = 0.454 ft. per sec.



4

$V_o$ = 0.200 ft. per sec.



5

$V_o$ = 0.050 ft. per sec.

PLATE 6. FLOW PATTERNS AT A SUPERFICIAL WATER VELOCITY OF 0.10 FT. PER SEC.



6

$V_o$ = 1.95 ft. per sec.



7

$V_o$ = 1.11 ft. per sec.



8

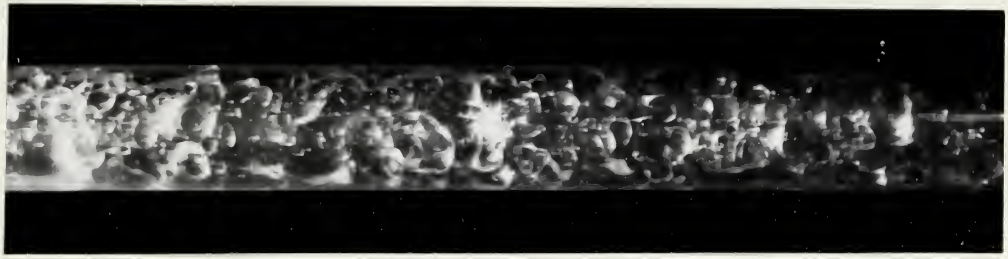
$V_o$ = 0.682 ft. per sec.



9

$V_o$ = 0.200 ft. per sec.

PLATE 7. FLOW PATTERNS AT A SUPERFICIAL WATER VELOCITY OF 0.682 FT. PER SEC.



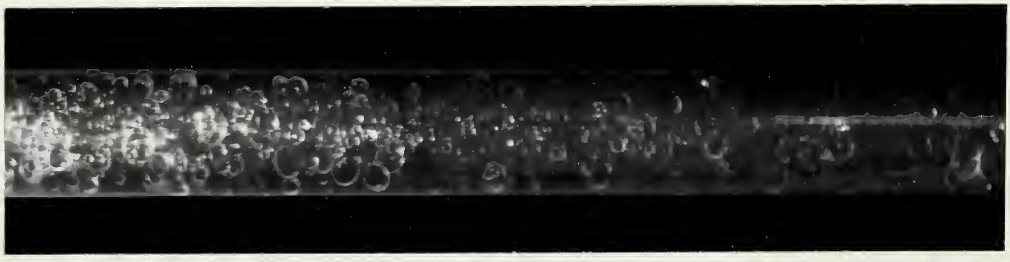
10

$V_o$= 1.82 ft. per sec.



11

$V_o$= 0.682 ft. per sec.

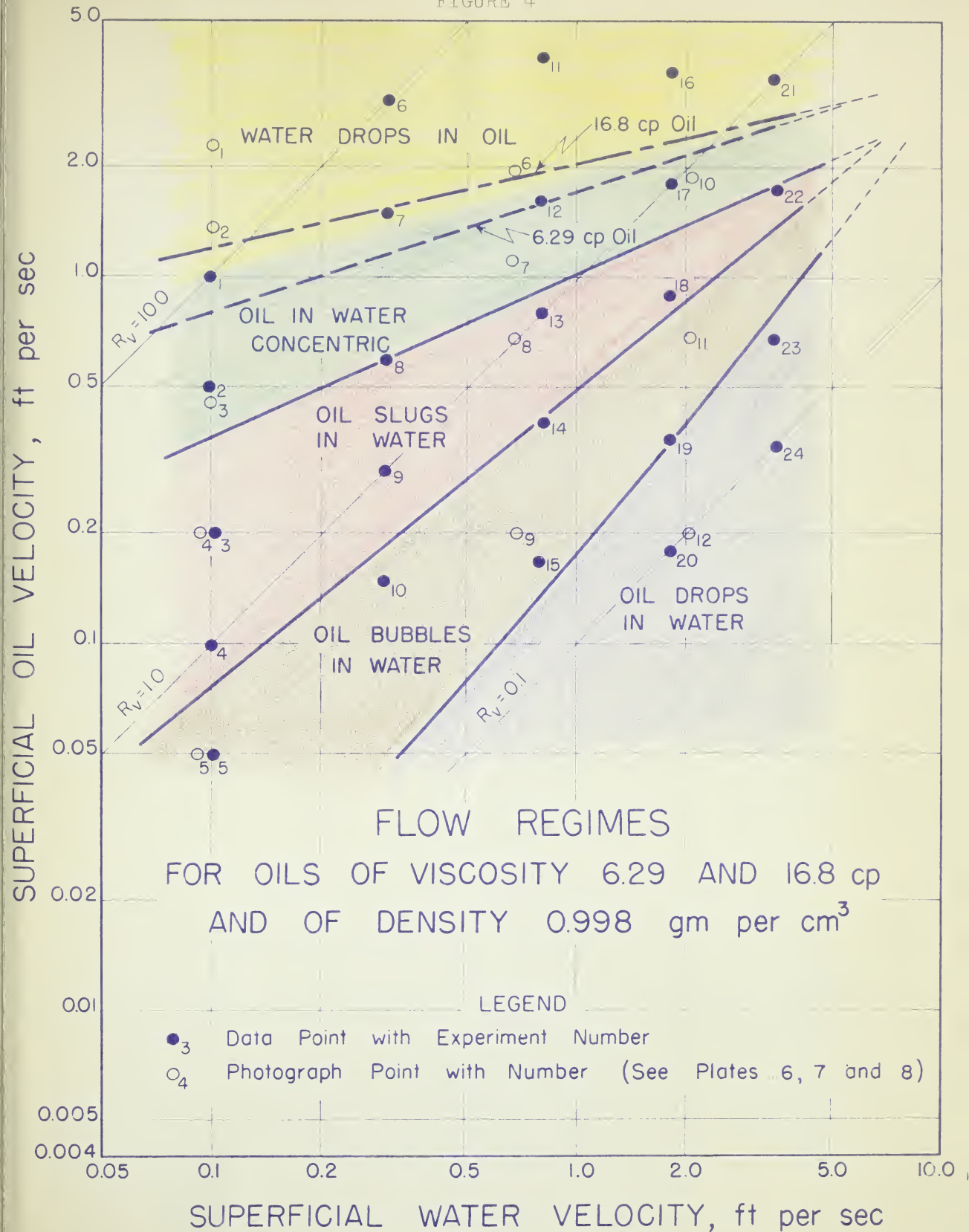


12

$V_o$= 0.200 ft. per sec.

PLATE 8. FLOW PATTERNS AT A SUPERFICIAL WATER VELOCITY OF 2.04 FT. PER SEC.

FIGURE 4




# FLOW REGIMES

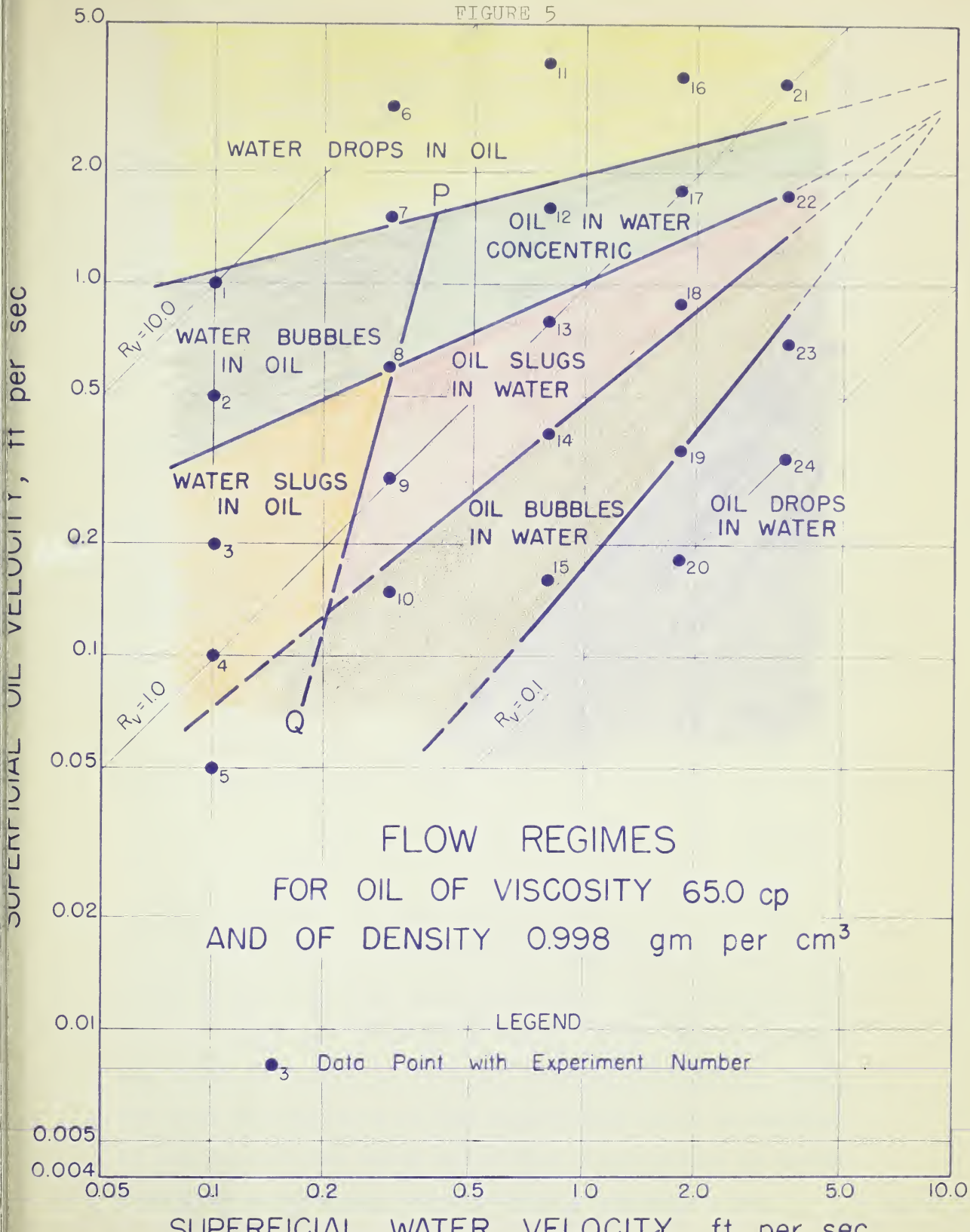
## FOR OILS OF VISCOSITY 6.29 AND 16.8 cp AND OF DENSITY 0.998 gm per $cm^3$

LEGEND

●$_3$ Data Point with Experiment Number

○$_4$ Photograph Point with Number (See Plates 6, 7 and 8)

FIGURE 5




# FLOW REGIMES

## FOR OIL OF VISCOSITY 65.0 cp AND OF DENSITY 0.998 gm per $cm^3$

LEGEND

3 Data Point with Experiment Number

co-ordinates and single lines are drawn between the various flow regimes. The change from one regime to another was not well defined and the lines represent gradual transitions. The oil and water superficial velocities for which experiments were performed are plotted with the corresponding experiment number in both Figures 4 and 5 whilst the superficial velocities for which photographs were taken are plotted with the corresponding photograph number in Figure 4.

The flow regimes for the least viscous oils are almost identical. The only difference occurs in the position of the boundary between the 'water drops in oil' and the 'oil in water concentric' flow regimes. The boundary is at a higher superficial oil velocity for the 16.8 cp. oil than for the 6.29 cp. oil. This could possibly be accounted for by the higher viscosity of the 16.8 cp. oil but the more viscous 65.0 cp. oil did not continue the trend.

The flow regime boundaries tend to converge to a point represented by a superficial oil velocity of 3.5 ft. per sec. and a superficial water velocity of 10 ft. per sec. It is possible that at greater superficial oil and water velocities the flow is completely mixed and that this type of flow is an intermediate between the 'water drops in oil' and 'oil drops in water' flow patterns.

The flow regimes observed for the 65.0 cp. oil are shown in Figure 5. This oil behaved differently from the less viscous oils at low superficial water velocities. At low superficial water velocities a succession of different flow patterns was obtained with the oil as the

continuous phase. The line PQ is the inversion line; for a given superficial oil velocity a superficial water velocity of less than that represented by the inversion line gave a flow pattern with oil as the continuous phase, whilst for a superficial water velocity greater than that represented by the inversion line flow patterns with water as the continuous phase were obtained. The boundaries between the regimes in which water was the continuous phase were almost identical with the corresponding boundaries for the less viscous oils. The regime boundaries are represented by dashed lines at low oil and water superficial velocities because the flow patterns were not well defined under these conditions.

It is possible that the different behaviour of the 65.0 cp. oil at low superficial water velocities can be attributed to different interfacial properties of the oil when in contact with water. The most viscous oil was visually observed to spread readily on, and displace water from, the pipe surface whereas the less viscous oils were observed to maintain a definite angle of contact with the pipe surface in the presence of water. As the first stage in ascertaining whether the interfacial properties of the three oils in contact with water were significantly different the interfacial tensions were measured and this work is reported in Appendix D. Table D3 shows that the interfacial tensions of the 6.29 and the 16.8 cp. oils in contact with water were 44 and 45 dynes per cm. and

that the interfacial tension of the 65.0 cp. oil in contact with water was 30 dynes per cm. These interfacial tensions are probably correct to within 5-10%. It is suggested that quantitive measurements of oil contact angles on the pipe surface in the presence of water would further illustrate the apparently different interfacial properties. Different interfacial properties would not be surprising because the 6.29 and the 16.8 cp. oils were both prepared from white mineral oils whilst the 65.0 cp. oil was prepared from a lubricating oil containing anti-corrosion compounds.

The flow patterns observed in this study are related to the flow patterns reported by Russell et al (7). Russell et al in their study of the flow of oil and water of different densities noted three flow patterns:

1. bubble flow, in which oil drops and bubbles moved along the top of the pipe.
2. stratified flow, in which the oil and water flowed in two layers with a quiet interface.
3. mixed flow, which occurred at high flow rates and was a completely mixed type of flow.

The bubble flow of Russell corresponds to the 'oil drops in water' and 'oil bubbles in water' flow patterns observed in the present study. The stratified flow corresponds to the 'oil in water concentric' flow pattern and the mixed flow to the 'water drops in oil' flow pattern.

A circulation of oil within the bubbles and slugs was noted for the 'oil slugs in water' and 'oil bubbles in water' flow patterns. This movement is indicated

in Figure 6 for bubble flow. The arrows represent approximate velocities relative to the average flow velocity. The direction of rotation of the bubble is probably dependent on the direction of a small density differential between the oil and the water. When the oil is slightly more dense than the water the bubble would tend to drag more at the lower surface of the pipe and rotate in the direction shown. A circulatory movement was also noted in the water phase between the bubbles or slugs of oil.

Pressure drop data

The pressure drops were recorded for the 6.29, 16.8 and 65.0 cp. viscosity oils for various superficial oil velocities at superficial water velocities of 0.1, 0.3, 0.8, 1.8 and 3.5 ft. per sec. The pressure drops obtained for the three oils are recorded in tabular form in Tables B2, B3 and B4. The reproducibility of pressure drop measurements was tested by recording three pressure drops in each experiment with the 6.29 cp. viscosity oil. The three pressure drops with the average pressure drop are given in Table B2 and, in general, the three pressure drop readings are in good agreement. Consequently only one pressure drop measurement was recorded in each experiment with the more viscous oils. The calculated modified friction factors based on the water properties are given in Tables C1, C2 and C3.

The modified friction factors are plotted against input oil-water ratio with superficial water velocity as

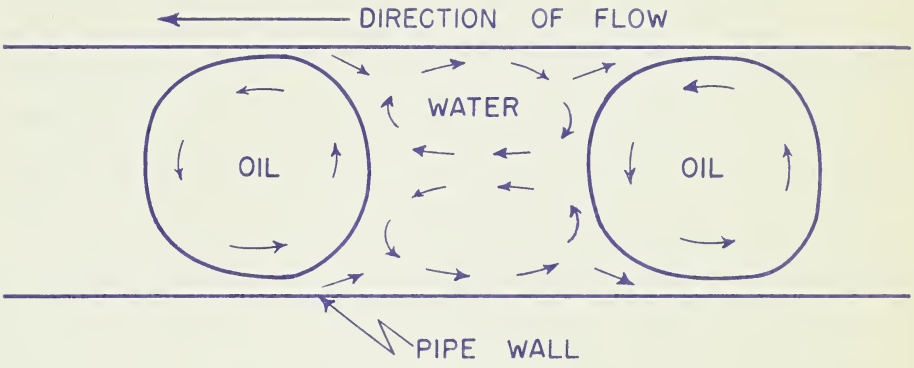



FIGURE 6

LIQUID MOVEMENT IN BUBBLE FLOW

parameter for the 6.29 cp. viscosity oil in Figure 7, for the 16.8 cp. viscosity oil in Figure 8 and for the 65.0 cp. viscosity oil in Figure 9.

When a smooth family of curves was drawn through the data for each oil, the modified friction factors calculated for water flowing alone were given infinite weight.

In general the data fitted smooth curves showing, for a given superficial water velocity, an increase in friction factor with an increase in input ratio. Difficulty was experienced in fitting a curve to the data at a superficial water velocity of 0.1 ft. per sec. for the 6.29 and 16.8 cp. oils. Data were obtained for input oil-water ratios from 0.5 to 10.0 at a superficial water velocity of 0.1 ft. per sec. and these data are not represented by curves which fit into the families of curves representing the data for the higher superficial water velocities. No data were obtained for input oil-water ratios less than 0.5 at a superficial water velocity of 0.1 ft. per sec. However, at an input ratio less than 0.5 a large change in slope must take place so that the curve can approach with zero slope to an input ratio of zero. No explanation is offered of the apparently anomalous behavior at a superficial water velocity of 0.1 ft. per sec. of the 6.29 and 16.8 cp. viscosity oils. The data for a superficial water velocity of 0.1 ft. per sec. for the 65.0 cp. oil show good agreement with the data obtained at higher superficial water velocities.

At low input oil-water ratios water was the continuous phase and the modified friction factor curves for the three oils are almost identical. Hence when oil flows as the discontinuous phase the friction factor is largely independent of the oil viscosity.

At high input ratios the data for the least viscous oils are similar but the data for the 65.0 cp. oil show dissimilarity for experiments in which this oil was the continuous phase. The relatively high modified friction factors obtained for this oil are accounted for by the relatively high viscosity of the oil.

Two more points are worthy of mention. First, the dip, at an input ratio of 4.0, in the curve for a superficial water velocity of 0.1 ft. per sec. for the 6.29 cp. viscosity oil coincides with 'oil in water concentric' flow and indicates a relatively low pressure drop for this flow system. The dip in the curve for a superficial water velocity of 0.1 ft. per sec. for the 16.8 cp. oil is not so evident.

Second, the friction factor for the 65.0 cp. oil at a superficial water velocity of 0.3 ft. per sec. and an input ratio of 2.0 was highly variable because the flow pattern continually changed from one in which the oil was the continuous phase to one in which water was the continuous phase.

The smooth families of curves given in Figures 7, 8 and 9 were used to produce the cross plots given in

FIGURE 7

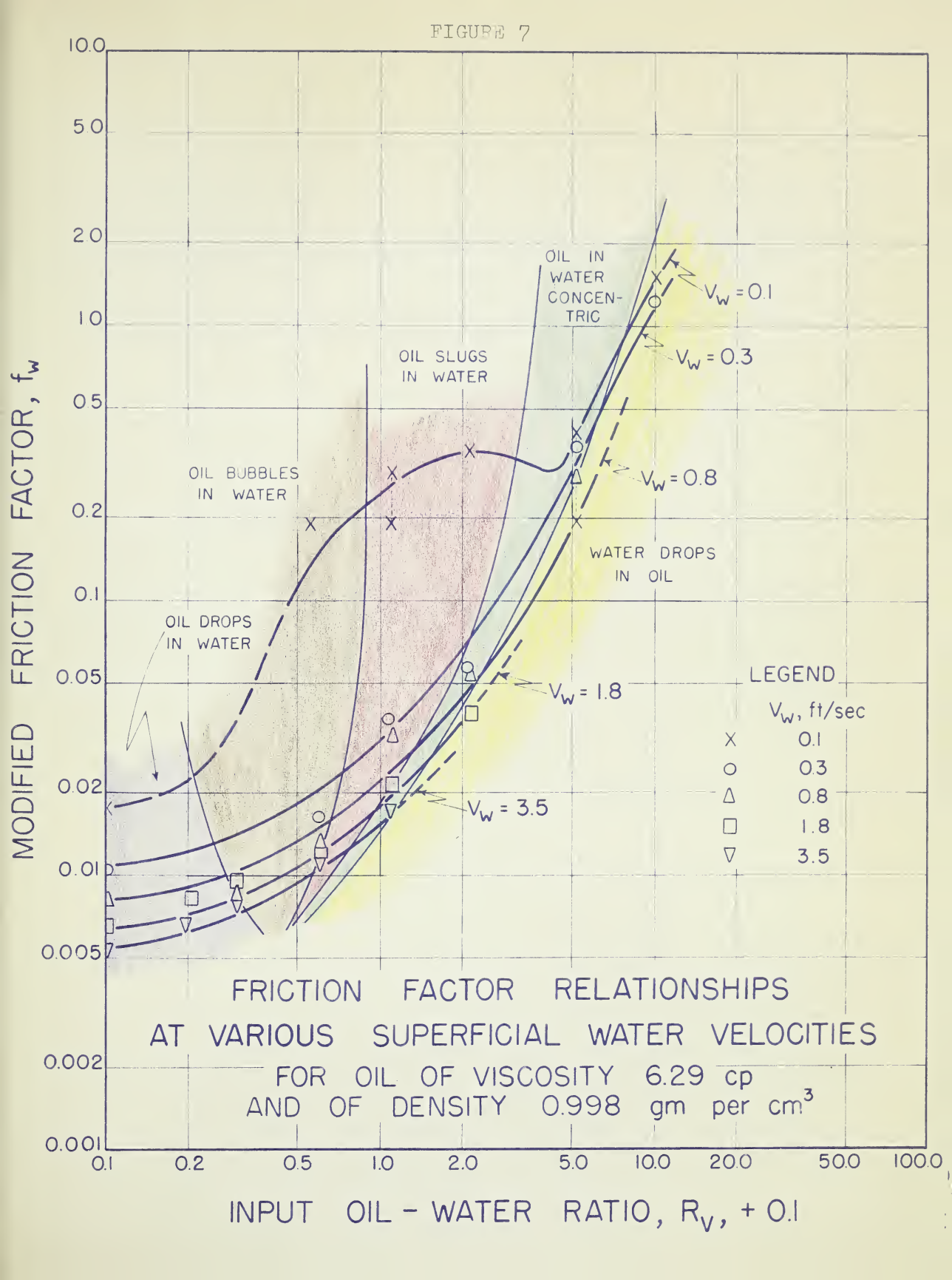
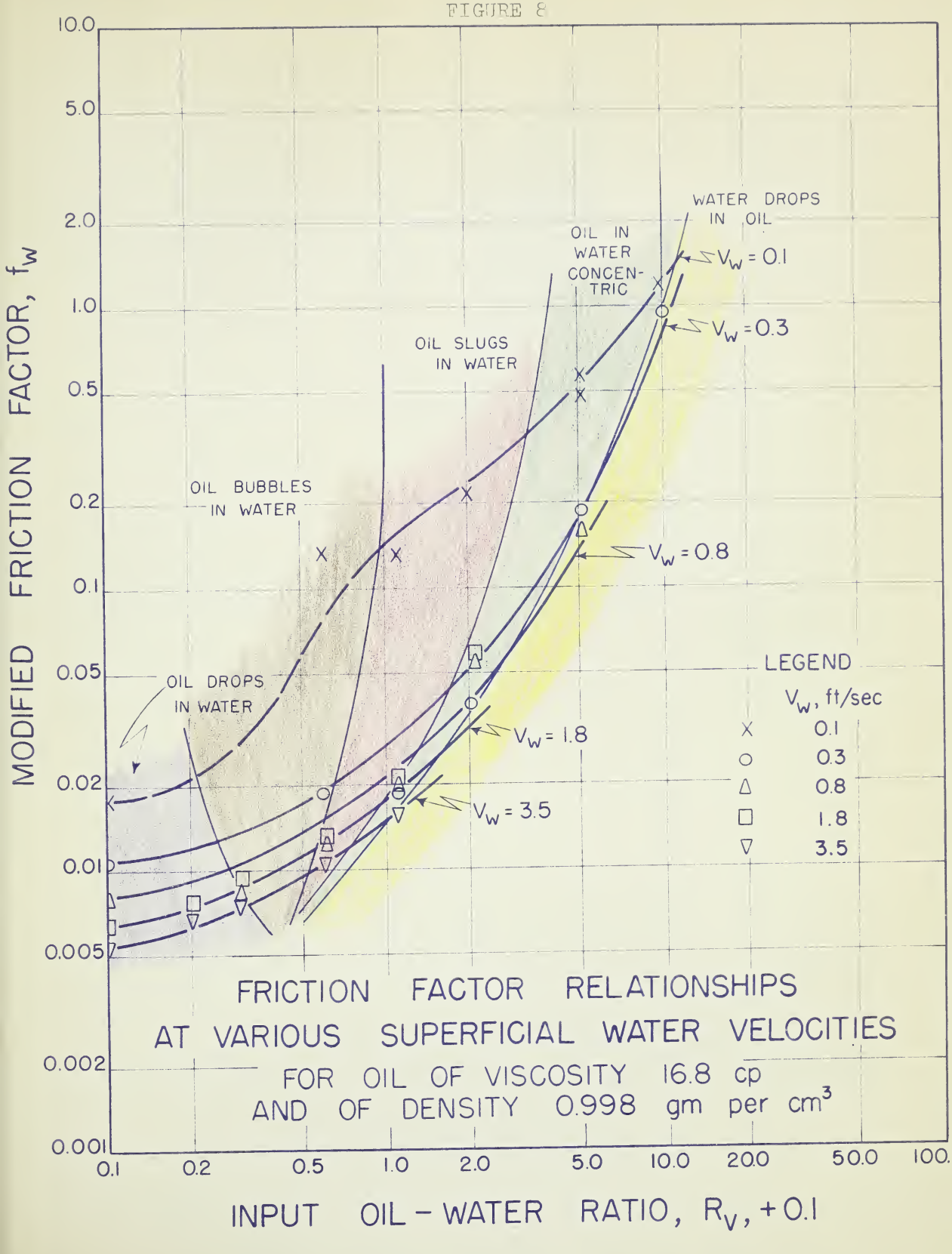
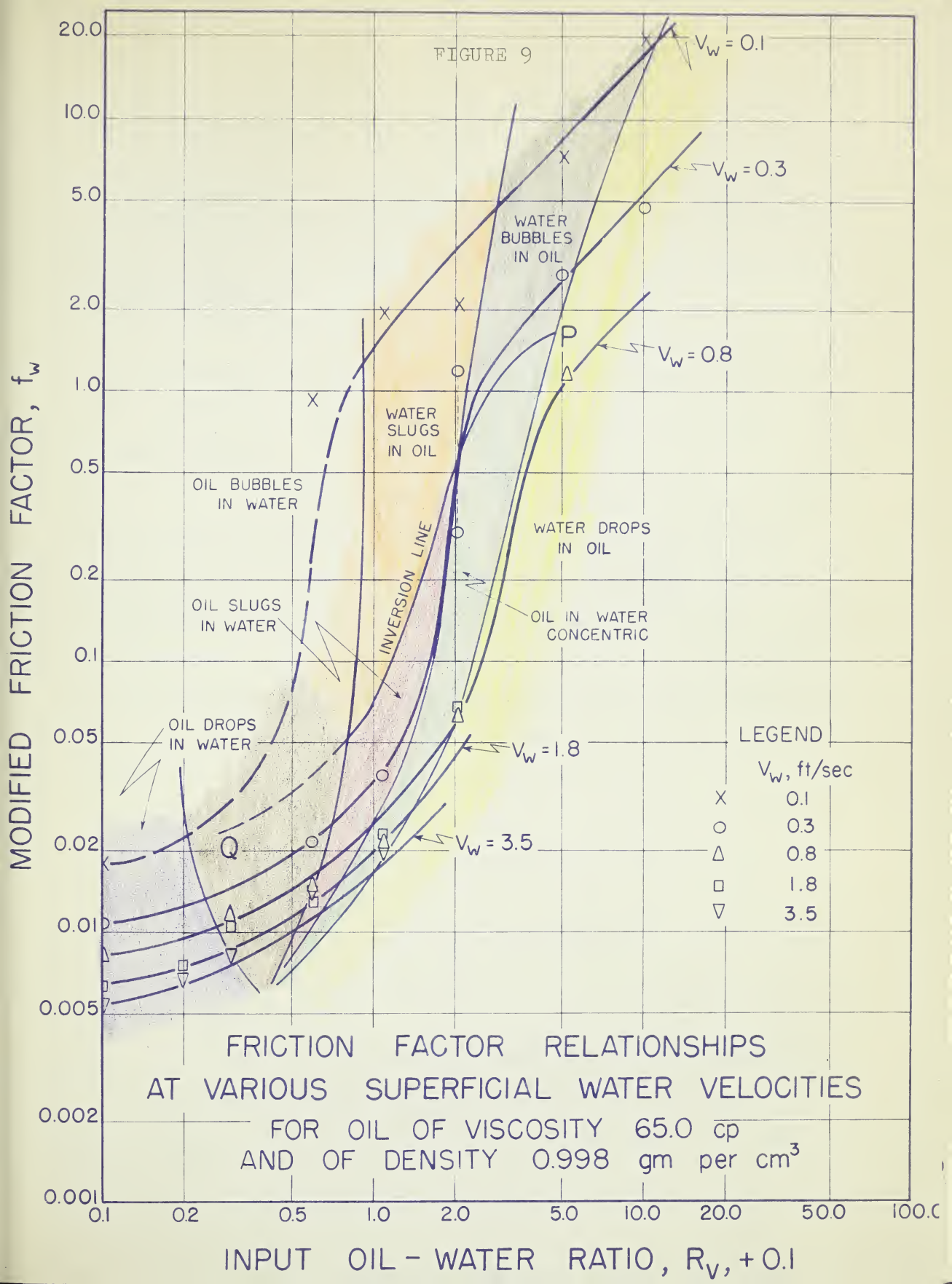

MODIFIED FRICTION FACTOR, $f_w$
10.0
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
OIL IN WATER CONCEN-TRIC
OIL SLUGS IN WATER
OIL BUBBLES IN WATER
OIL DROPS IN WATER
WATER DROPS IN OIL
$V_w$ = 0.1
$V_w$ = 0.3
$V_w$ = 0.8
$V_w$ = 1.8
$V_w$ = 3.5
LEGEND
$V_w$, ft/sec
X 0.1
○ 0.3
△ 0.8
□ 1.8
▽ 3.5
FRICTION FACTOR RELATIONSHIPS
AT VARIOUS SUPERFICIAL WATER VELOCITIES
FOR OIL OF VISCOSITY 6.29 cp
AND OF DENSITY 0.998 gm per $cm^3$
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
INPUT OIL - WATER RATIO, $R_v$, + 0.1

FIGURE 8




FRICTION FACTOR RELATIONSHIPS
AT VARIOUS SUPERFICIAL WATER VELOCITIES
FOR OIL OF VISCOSITY 16.8 cp
AND OF DENSITY 0.998 gm per $cm^3$


FIGURE 9
MODIFIED FRICTION FACTOR, $f_w$
INPUT OIL - WATER RATIO, $R_v$, + 0.1
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
$V_w$ = 0.1
$V_w$ = 0.3
$V_w$ = 0.8
$V_w$ = 1.8
$V_w$ = 3.5
WATER BUBBLES IN OIL
WATER SLUGS IN OIL
OIL BUBBLES IN WATER
INVERSION LINE
WATER DROPS IN OIL
OIL IN WATER CONCENTRIC
OIL SLUGS IN WATER
OIL DROPS IN WATER
P
Q
LEGEND
$V_w$, ft/sec
X 0.1
○ 0.3
△ 0.8
□ 1.8
▽ 3.5
FRICTION FACTOR RELATIONSHIPS
AT VARIOUS SUPERFICIAL WATER VELOCITIES
FOR OIL OF VISCOSITY 65.0 cp
AND OF DENSITY 0.998 gm per cm$^3$

Figures 10, 11 and 12 where the modified friction factors are plotted against superficial water velocity with input oil-water ratio as parameter. The data for the 6.29 cp. viscosity oil are represented in Figure 10; for the 16.8cp. viscosity oil in Figure 11 and for the 65.0 cp. viscosity oil in Figure 12.

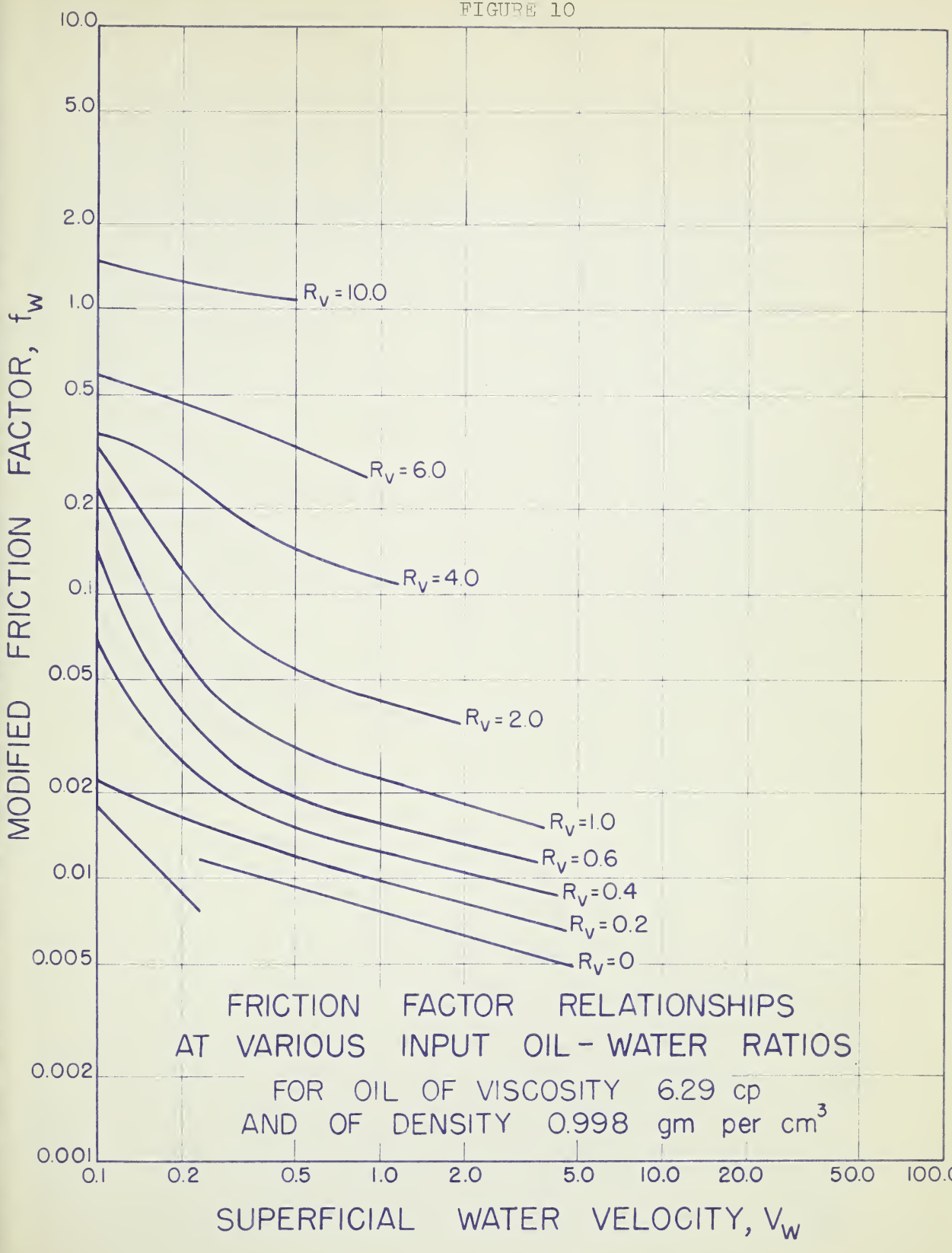
The similarity of the data for the three oils at low input oil-water ratios, and the different behavior of the 65.0 cp. viscosity oil at high input ratios is again evident.

In general, the data for the least viscous oils are similar. However, for a given input oil-water ratio the friction factors for the 16.8 cp. viscosity oil are less than those for the 6.29 cp. viscosity oil. The difference is most apparent at input ratios of 4.0, 6.0 and 10.0 and indicates that for these input ratios and a given superficial water velocity the pressure drop is less for the 16.8 cp. oil than for the 6.29 cp. oil. Although the more viscous oil would be expected to give the higher pressure drops the apparent anomaly is explained by the existence of 'oil in water concentric' flow at higher superficial oil velocities for the 16.8 cp. oil than for the 6.29 cp. oil.

Holdup Data

Holdup ratios, calculated for each experiment by dividing the input oil-water ratio by the in situ oil-water ratio, are presented in Tables C1, C2, C3. The

FIGURE 10




FRICTION FACTOR RELATIONSHIPS
AT VARIOUS INPUT OIL - WATER RATIOS
FOR OIL OF VISCOSITY 6.29 cp
AND OF DENSITY 0.998 gm per $cm^3$

FIGURE 11

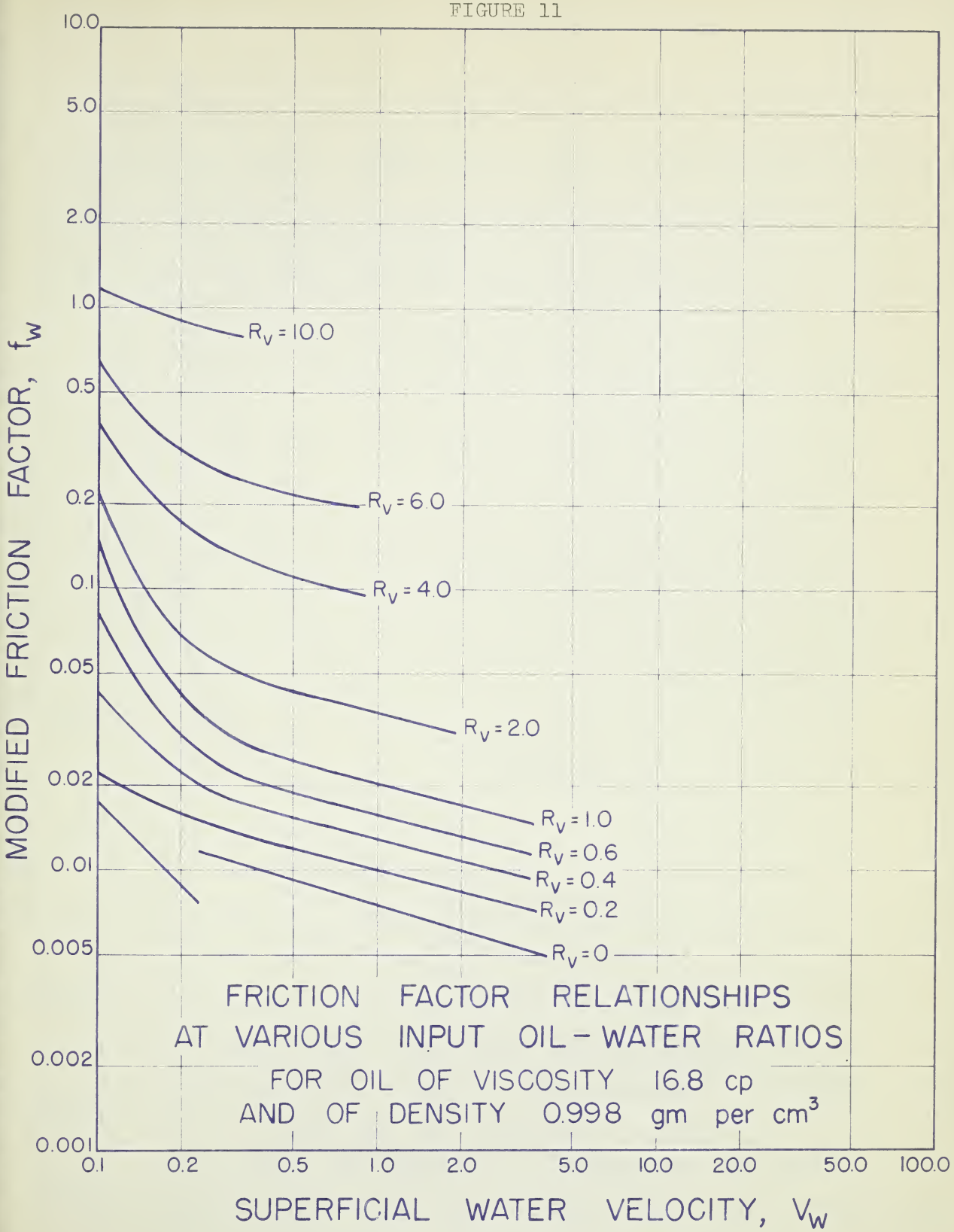
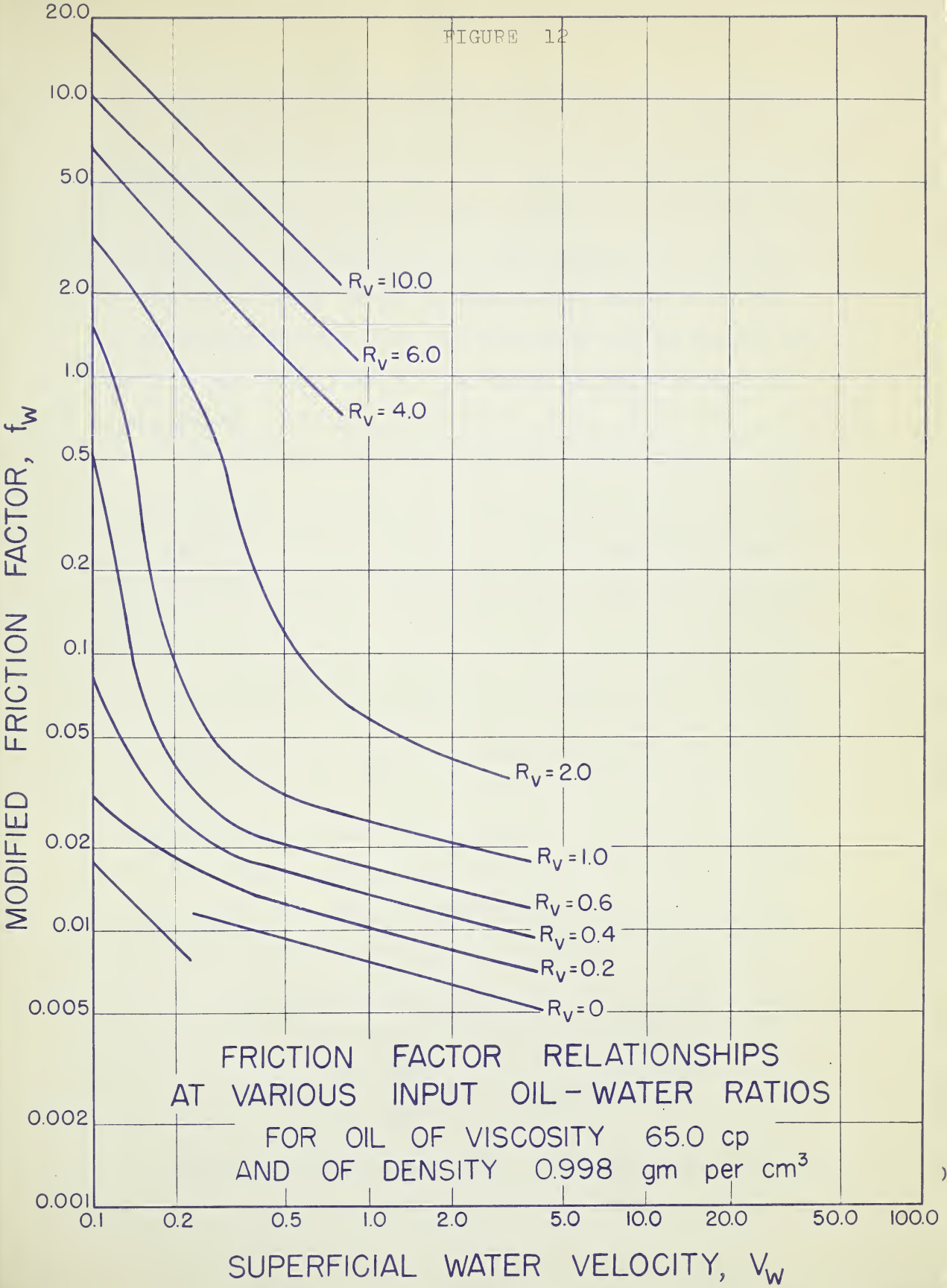

10.0
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
MODIFIED FRICTION FACTOR, $f_w$
$R_V = 10.0$
$R_V = 6.0$
$R_V = 4.0$
$R_V = 2.0$
$R_V = 1.0$
$R_V = 0.6$
$R_V = 0.4$
$R_V = 0.2$
$R_V = 0$
FRICTION FACTOR RELATIONSHIPS
AT VARIOUS INPUT OIL – WATER RATIOS
FOR OIL OF VISCOSITY 16.8 cp
AND OF DENSITY 0.998 gm per $cm^3$
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
SUPERFICIAL WATER VELOCITY, $V_w$

FIGURE 12




FRICTION FACTOR RELATIONSHIPS
AT VARIOUS INPUT OIL – WATER RATIOS
FOR OIL OF VISCOSITY 65.0 cp
AND OF DENSITY 0.998 gm per $cm^3$

reproducibility of the holdup ratio was tested by making two measurements in each experiment with the 6.29 cp. viscosity oil. The agreement was good and only one holdup measurement was made in each experiment with the more viscous oils. The holdup ratios are shown as a function of the input ratio with the superficial water velocity as parameter for the 6.29 cp. viscosity oil in Figure 13, the 16.8 cp. viscosity oil in Figure 14 and the 65.0 cp. viscosity oil in Figure 15.

A holdup ratio greater than unity indicates an accumulation of water in the pipeline relative to the input ratio and a holdup ratio less than unity indicates an accumulation of oil in the pipeline relative to the input ratio.

In general, the curves for the three oils are similar in that, for a given superficial water velocity, the curves pass through maxima which coincide with the 'oil in water concentric' flow pattern. This indicates a relatively high accumulation of water in the pipeline for this flow system and is explained since the water is next to the pipe wall and is flowing with a lower average velocity than that of the oil.

The theoretical holdup ratio for laminar 'oil in water concentric' flow is given by equation (8) as:

$$H_R = 2.00 + \frac{\mu_w}{\mu_o} \text{ (in situ ratio)}$$

For $\mu_w$ = 0.894 cp. and $\mu_o$ = 6.29 cp. and the in situ

ratio of 2.48 recorded in experiment 102:

$$H_R = 2.00 + \frac{0.894}{6.29} \cdot 2.48 = 2.35.$$

A similar calculation for $\mu_o$ = 16.8 cp. and the in situ ratio of 3.07 recorded in experiment 202 gives a theoretical holdup ratio of 2.16.

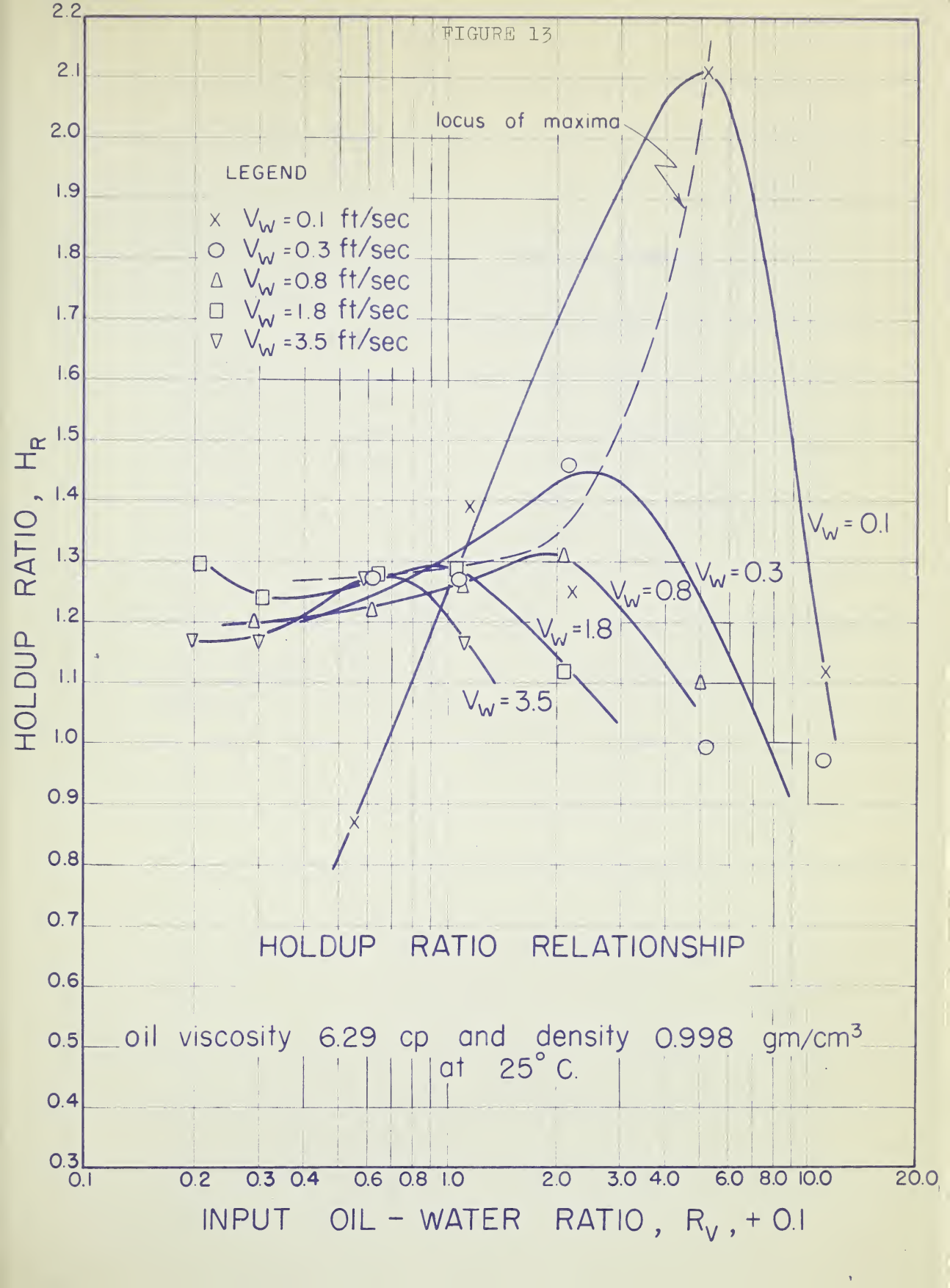
These theoretical holdup ratios compare with the values 2.11 and 1.66 obtained in experiments 102 and 202 respectively. The difference between the theoretical and experimental holdup ratios is probably accounted for by the experimental flow systems not being perfectly concentric. A water annulus of varying thickness would tend to lower the holdup ratio. The laminar 'oil in water concentric' flow pattern was not obtained for the 65.0 cp. viscosity oil in experiment 302.

Although in general the holdup curves obtained for the three oils are similar the holdup ratios recorded at superficial water velocities of 0.1 and 0.3 ft. per sec. for the 65.0 cp. oil differ considerably from those for the less viscous oils. At these superficial water velocities the most viscous oil gave holdup ratios of approximately 0.6 for the flow patterns in which the oil formed the continuous phase.

A general conclusion from the holdup data is, that at low input oil-water ratios, the holdup ratio is less dependent on the superficial water velocity than at high input oil-water ratios. With one exception (experi-

ment 105) the noldup ratios obtained for input oil-water ratios less than 1.0 fall in the range 1.0 to 1.3.

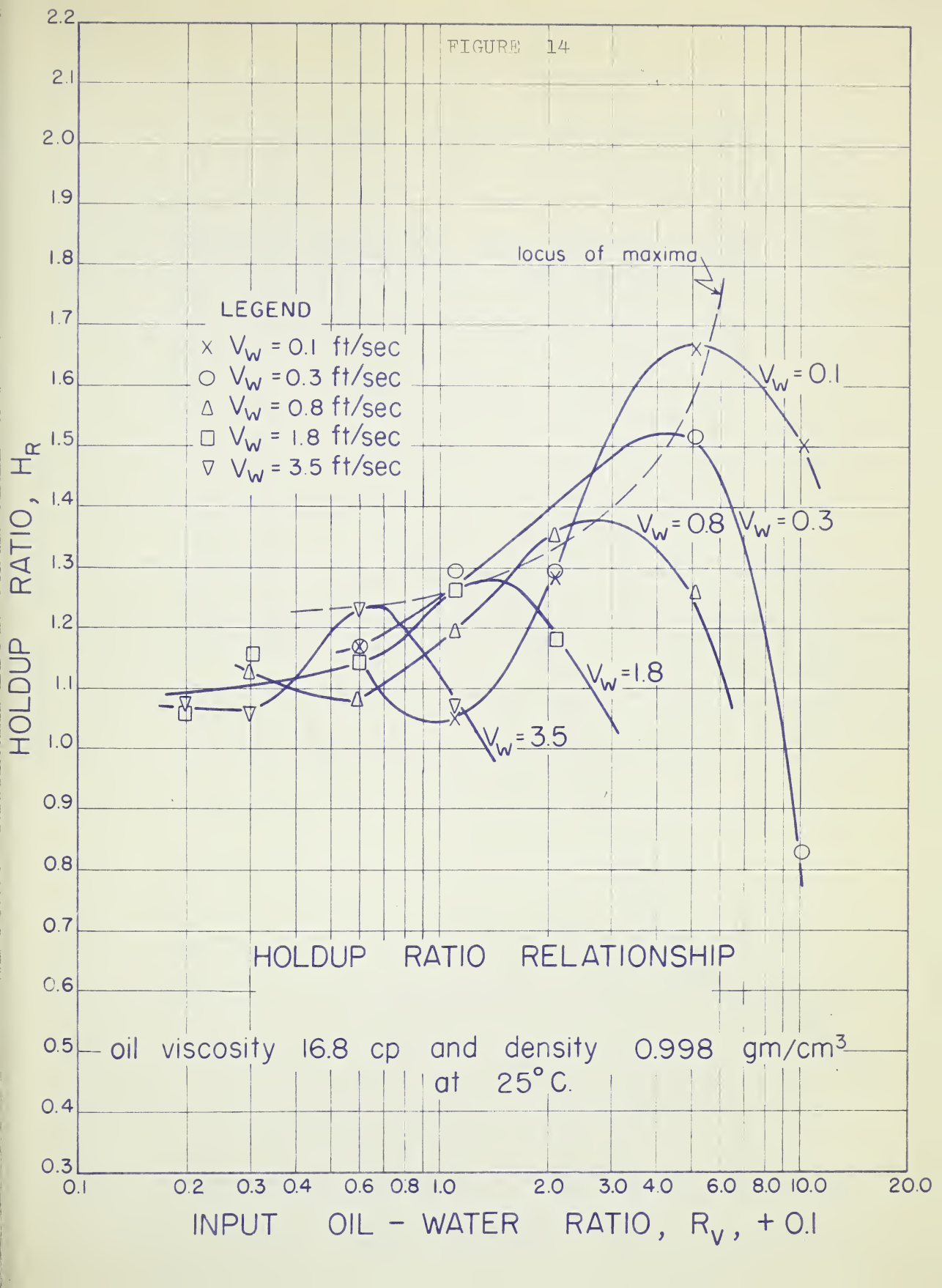
FIGURE 13




HOLDUP RATIO RELATIONSHIP

oil viscosity 6.29 cp and density 0.998 gm/cm$^3$ at 25° C.

FIGURE 14



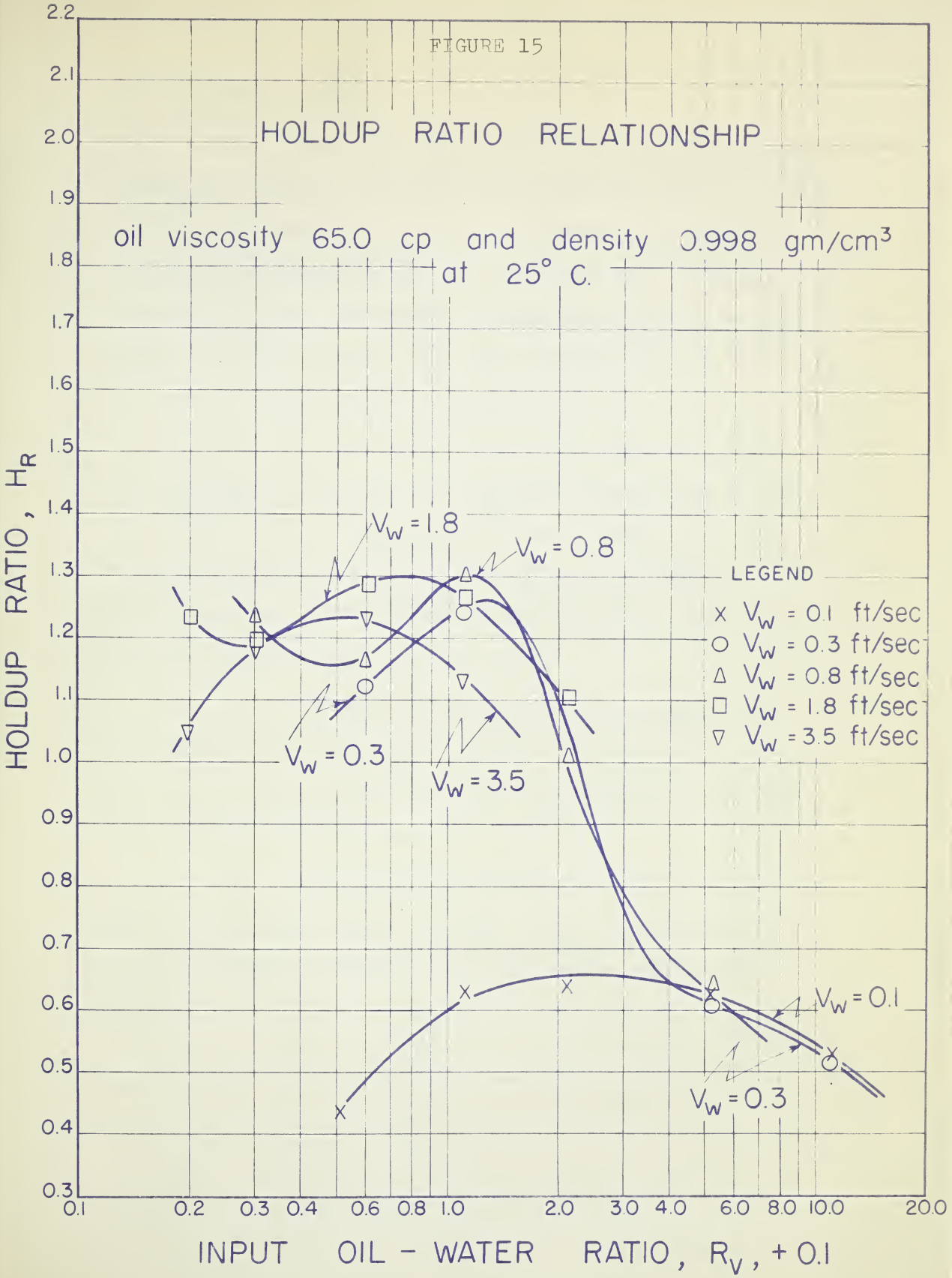

HOLDUP RATIO RELATIONSHIP

oil viscosity 16.8 cp and density 0.998 gm/cm$^3$ at 25° C.

FIGURE 15

# HOLDUP RATIO RELATIONSHIP

oil viscosity 65.0 cp and density 0.998 gm/cm³ at 25° C.



## CONCLUSIONS

1. The flow patterns for the equal density horizontal flow of oil-water mixtures were found to be largely independent of the oil viscosity for the three oils of viscosities 6.29, 16.8 and 65.0 cp., although the most viscous oil showed dissimilar behavior at high input oil-water ratios. This was probably due to different oil-water interfacial properties.

2. At low input oil-water ratios the pipeline pressure gradients were largely independent of the oil viscosity. At high oil-water input ratios the more viscous oil gave relatively high pressure gradients in the regimes of flow where the oil formed the continuous phase in contact with the pipe wall.

3. For given superficial water velocities the curves for holdup ratio plotted against input oil-water ratio pass through maxima which coincide with the 'oil in water concentric' flow regime.

4. The anomalous behavior of the most viscous oil at high input oil-water ratios was reflected in flow pattern, pressure drop and holdup ratio observations.

# A P P E N D I C E S

# APPENDIX A

## CALIBRATION DATA

1. Rotameter calibration.
2. Measurement of pipeline diameter.
3. Check of pipeline operation.

1. Rotameter Calibration

The oil and water rotameters were calibrated by weight-time measurements. Large and small rotameters were used for each liquid. Interchangeable steel and plastic floats were used with the large rotameters; only steel floats were used with the small rotameters. The calibration data are tabulated in the research notebook and are presented graphically in Figures A1, A2 and A3 in which the flow rate (lb. per min.) divided by the rotameter reading is plotted against the rotameter reading.

The water rotameter calibration curves are presented in Figure A1. The three curves represent:

(1) the calibration of the large rotameter (56-10-B-1097/1-2) with the steel float

(2) the calibration of the small rotameter (56-10-B-1097/3-4) with the steel float

and (3) the calibration of the large rotameter (56-10-1097/1-2) with the plastic float.

The oil rotameter calibration curves are presented in Figures A2 and A3. The two sets of curves in Figure A2 represent:

(1) the calibrations of the large rotameter (56-10-B-1097/1-2) with the steel float for the three oils of viscosities 6.29, 16.8 and 65.0 cp.

(2) the calibrations of the small rotameter (56-10-B-1097/3-4) with the steel float

for the three oils.

The curves presented in Figure A4 represent the calibrations of the large rotameter (56-10-D97/1-2) with the plastic float for the three oils.

2. Measurement of Pipeline Diameter

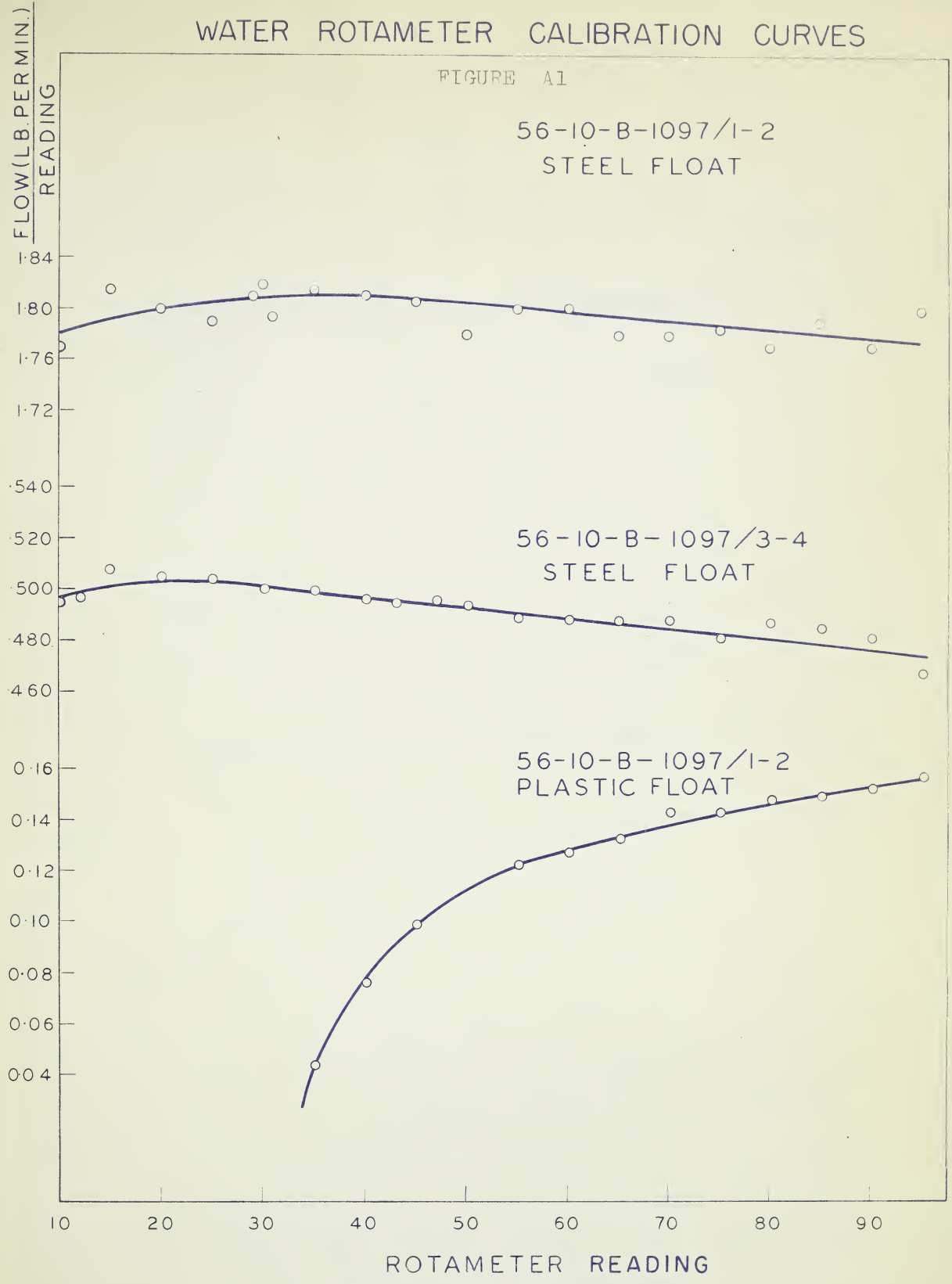
The internal diameter of the pipeline was determined with calipers. The diameter varied between 1.028 and 1.053 inches and thirty readings were averaged to give a pipe diameter of 1.040 inches.

3. Check of Pipeline Operation

The rotameter calibrations, the pipeline diameter and the operation of the pressure drop measuring equipment were checked by taking pressure drop measurements for the oils and water flowing alone. The pressure drops and calculated friction factors are tabulated in the research notebook and are presented here graphically in Figure A4 where the Fanning friction factors are plotted against Reynolds number. Also plotted are the curves $f = \frac{16}{Re}$ for the laminar region of flow and the Blasius equation for the turbulent region. Good agreement is evident between the experimental data and the accepted curves.

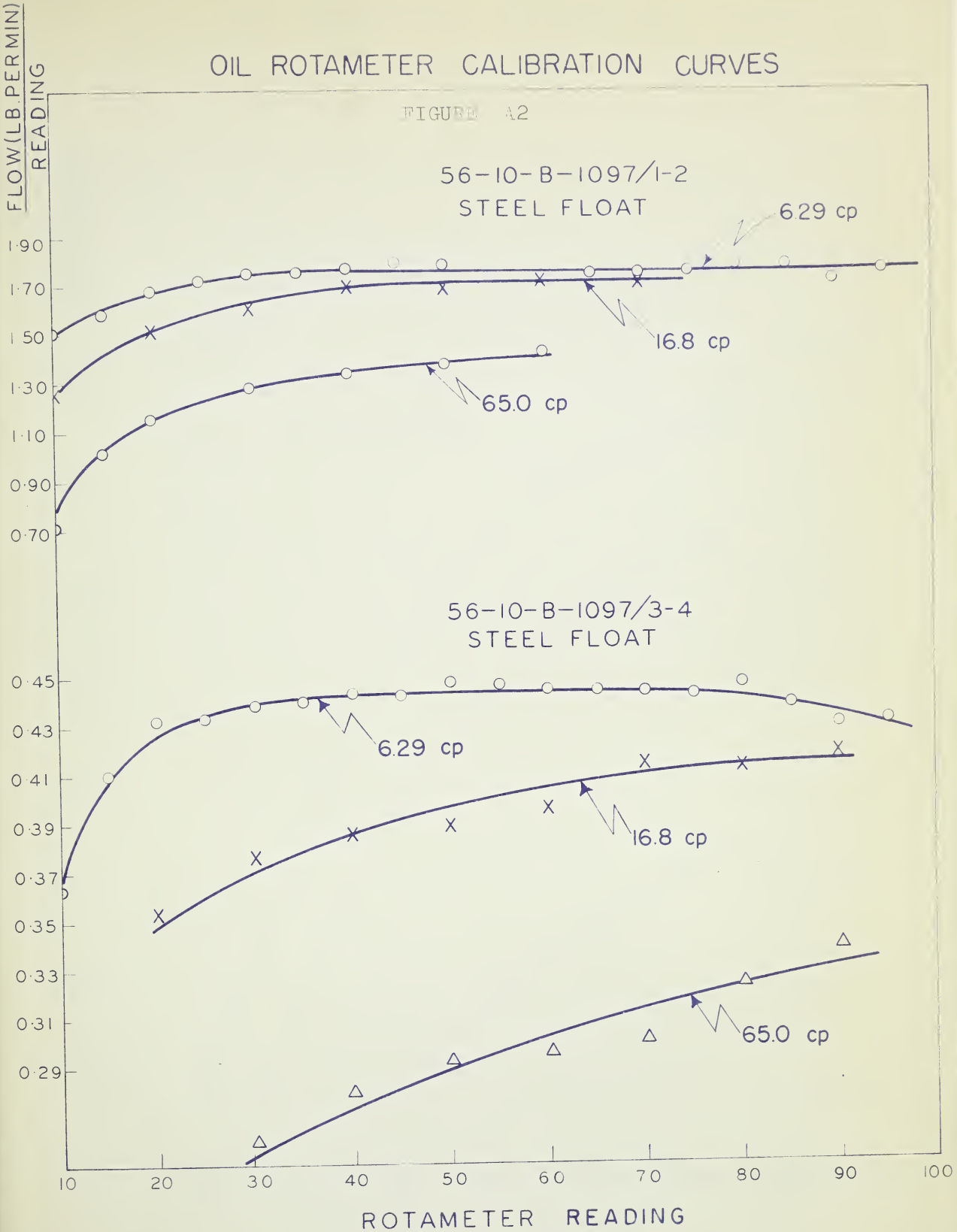
# WATER ROTAMETER CALIBRATION CURVES

FIGURE A1



# OIL ROTAMETER CALIBRATION CURVES

FIGURE A2



# OIL ROTAMETER CALIBRATION CURVES

FIGURE A3

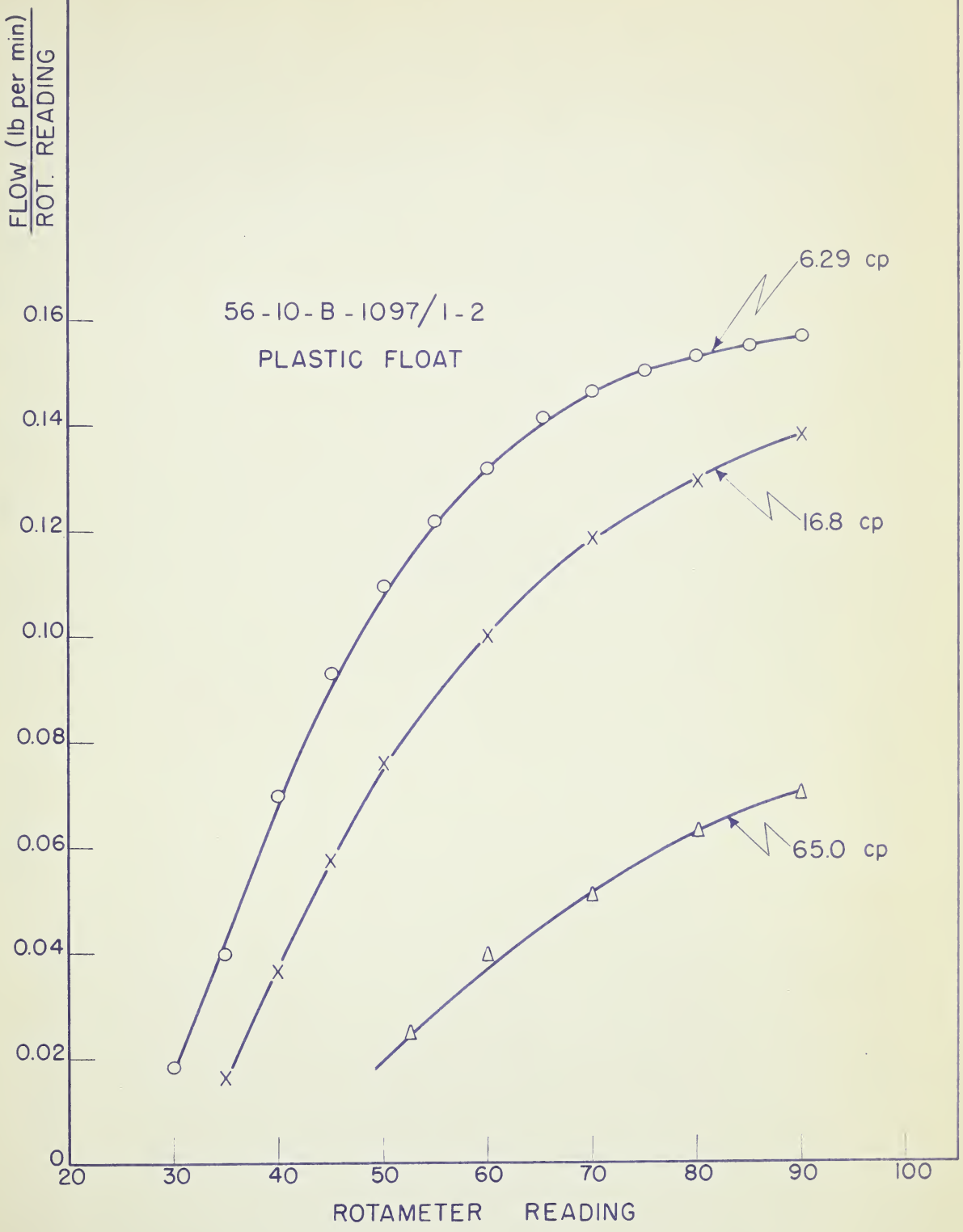
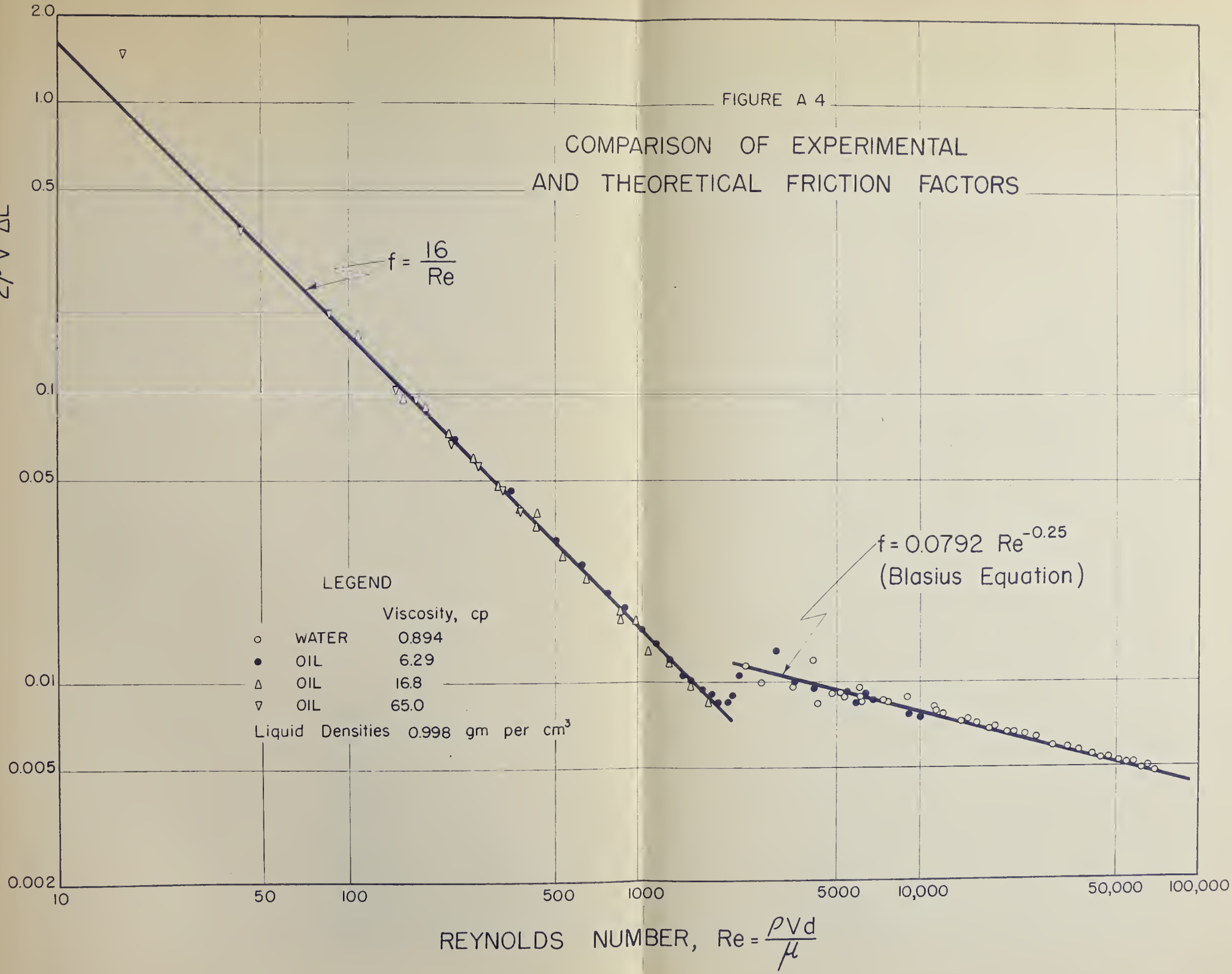


FIGURE A 4

# COMPARISON OF EXPERIMENTAL AND THEORETICAL FRICTION FACTORS



# APPENDIX B

# EXPERIMENTAL DATA

## EXPERIMENTAL DATA

The properties of the test oils and the dimensions of the pipeline test section are given in Table B1.

The experimental data for the test oils flowing in the presence of water are tabulated for the 6.29 cp. viscosity oil in Table B2, for the 16.8 cp. viscosity oil in Table B3 and for the 65.0 cp. viscosity oil in Table B4. The tables give, for a given experiment number, the oil and water superficial velocities in ft. per sec., the pressure drop over the test section in inches of water and the in situ oil-water ratio.

Experiment numbers begin with a one for the 6.29 cp. oil, with a two for the 16.8 cp. viscosity oil and with a three for the 65.0 cp. viscosity oil.

The three pressure drops and two in situ ratios, reported in Table B2, for the 6.29 cp. viscosity oil were recorded to test the reproducibility of the measurements. The reproducibility was good and only single measurements were subsequently made for the more viscous oils.

TABLE B1

GENERAL DATA

| | |
|---|---|
| Flowing temperature | 25 ± 0.5° C. |
| Water viscosity @ 25° C. | 0.894 cp. |
| Test oil viscosities @ 25° C. | 6.29, 16.8 and 65.0 cp. |
| Liquid densities @ 25° C. | 0.998gm.per cc. |
| Pipeline diameter | 1.040 in. |
| Length of pipeline for holdup measurements | 28.3 ft. |
| Length of pipeline between pressure stations | 24.0 ft. |
| Volume of pipeline for holdup measurements | 4720 cc. |

TABLE B2

EXPERIMENTAL DATA FOR 6.29 cp. VISCOSITY OIL

| Experiment number | Superficial water velocity | Superficial oil velocity | Pressure drop over test section | | | Average pressure drop | In situ ratio | |
|---|---|---|---|---|---|---|---|---|
| - | ft./sec. | ft./sec. | inches of water | | | inches of water | - | |
| | | | (1) | (2) | (3) | | (1) | (2) |
| 101 | 0.10 | 0.996 | 3.30 | 3.10 | 2.80 | 3.10 | 8.53 | 9.34 |
| 102 | 0.10 | 0.511 | 0.40 | to | 0.80 | 0.40-0.80 | 2.32 | 2.54 |
| 103 | 0.10 | 0.211 | 0.75 | 0.74 | 0.70 | 0.73 | 1.63 | 1.75 |
| 104 | 0.10 | 0.104 | 0.40 | to | 0.60 | 0.40-0.60 | 0.712 | 0.775 |
| 105 | 0.10 | 0.045 | 0.42 | 0.42 | 0.35 | 0.40 | 0.516 | 0.533 |
| 106 | 0.30 | 2.99 | 24.2 | 23.3 | 21.9 | 23.1 | 10.2 | 10.3 |
| 107 | 0.30 | 1.49 | 7.20 | 6.90 | 6.90 | 7.00 | 5.02 | 5.05 |
| 108 | 0.30 | 0.611 | 1.11 | 1.10 | 1.00 | 1.07 | 1.38 | 1.49 |
| 109 | 0.30 | 0.295 | 0.75 | 0.72 | 0.60 | 0.69 | 0.762 | 0.788 |
| 110 | 0.30 | 0.154 | 0.30 | 0.30 | 0.30 | 0.30 | 0.402 | 0.407 |
| 111 | 0.80 | 3.90 | 39.4 | 39.0 | 38.8 | 39.1 | 4.47 | 4.50 |
| 112 | 0.80 | 1.59 | 7.80 | 7.00 | 6.50 | 7.1 | 1.47 | 1.59 |
| 113 | 0.80 | 0.796 | 3.05 | 3.00 | 2.90 | 3.0 | 0.800 | 0.810 |
| 114 | 0.80 | 0.407 | 2.00 | 2.00 | 1.98 | 1.99 | 0.423 | 0.423 |
| 115 | 0.80 | 0.154 | 1.20 | 1.15 | 1.10 | 1.15 | 0.161 | 0.161 |
| 116 | 1.80 | 3.59 | 26.9 | 26.8 | 24.3 | 26.0 | 1.77 | 1.80 |
| 117 | 1.80 | 1.77 | 15.2 | 14.2 | 13.95 | 14.45 | 0.756 | 0.792 |
| 118 | 1.80 | 0.916 | 8.70 | 8.60 | 8.30 | 8.50 | 0.398 | 0.399 |
| 119 | 1.80 | 0.363 | 6.35 | 6.30 | 6.20 | 6.28 | 0.162 | 0.167 |
| 120 | 1.80 | 0.190 | 5.50 | 5.37 | 5.35 | 5.40 | 0.081 | 0.083 |
| 121 | 3.50 | 3.49 | 44.9 | 43.5 | 43.4 | 43.9 | 0.851 | 0.870 |
| 122 | 3.50 | 1.77 | 29.1 | 28.3 | 28.2 | 28.5 | 0.394 | 0.407 |
| 123 | 3.50 | 0.698 | 20.6 | 19.9 | 18.2 | 19.6 | 0.168 | 0.173 |
| 124 | 3.50 | 0.340 | 17.6 | 17.6 | 16.9 | 17.4 | 0.081 | 0.085 |

TABLE B3

EXPERIMENTAL DATA FOR 16.8 cp. VISCOSITY OIL

| Experiment number | Superficial water velocity | Superficial oil velocity | Pressure drop over test section | In situ ratio |
|---|---|---|---|---|
| - | ft./sec. | ft./sec. | inches of water | - |
| 201 | 0.10 | 1.00 | 2.5 | 6.68 |
| 202 | 0.10 | 0.50 | 1.0-1.2 | 3.07 |
| 203 | 0.10 | 0.200 | 0.45 | 1.56 |
| 204 | 0.10 | 0.100 | 0.30 | 0.958 |
| 205 | 0.10 | 0.050 | 0.30 | 0.428 |
| 206 | 0.30 | 3.00 | 17.6 | 12.1 |
| 207 | 0.30 | 1.50 | 3.45 | 3.26 |
| 208 | 0.30 | 0.60 | 0.70 | 1.55 |
| 209 | 0.30 | 0.30 | 0.35 | 0.775 |
| 210 | 0.30 | 0.15 | 0.35 | 0.426 |
| 211 | 0.80 | 3.98 | 21.0 | 3.97 |
| 212 | 0.80 | 1.60 | 7.20 | 1.48 |
| 213 | 0.80 | 0.80 | 2.55 | 0.840 |
| 214 | 0.80 | 0.40 | 1.60 | 0.463 |
| 215 | 0.80 | 0.159 | 1.10 | 0.178 |
| 216 | 1.80 | 3.60 | 39.2 | 1.70 |
| 217 | 1.80 | 1.80 | 14.2 | 0.796 |
| 218 | 1.80 | 0.90 | 8.70 | 0.440 |
| 219 | 1.80 | 0.358 | 6.20 | 0.174 |
| 220 | 1.80 | 0.182 | 5.20 | 0.094 |
| 221 | 3.50 | 3.50 | 40.0 | 0.953 |
| 222 | 3.50 | 1.75 | 27.3 | 0.407 |
| 223 | 3.50 | 0.693 | 19.6 | 0.189 |
| 224 | 3.50 | 0.350 | 17.5 | 0.094 |

TABLE B4

EXPERIMENTAL DATA FOR 65.0 cp. VISCOSITY OIL

| Experiment number | Superficial water velocity | Superficial oil velocity | Pressure drop over test section | In situ ratio |
|---|---|---|---|---|
| - | ft./sec. | ft./sec. | inches of water | - |
| 301 | 0.10 | 1.00 | 39.5 | 19.2 |
| 302 | 0.10 | 0.50 | 14.9 | 7.98 |
| 303 | 0.10 | 0.20 | 4.30 | 3.14 |
| 304 | 0.10 | 0.10 | 4.00 | 1.59 |
| 305 | 0.10 | 0.05 | 1.90 | 1.15 |
| 306 | 0.30 | 3.00 | 88.8 | 19.6 |
| 307 | 0.30 | 1.50 | 50.1 | 8.18 |
| 308 | 0.30 | 0.60 | 5.7-21.4 | * |
| 309 | 0.30 | 0.30 | 0.70 | 0.806 |
| 310 | 0.30 | 0.15 | 0.40 | 0.447 |
| 311 | 0.80 | 3.98 | 149.6 | 7.85 |
| 312 | 0.80 | 1.60 | 8.3 | 1.93 |
| 313 | 0.80 | 0.80 | 2.85 | 0.770 |
| 314 | 0.80 | 0.40 | 1.95 | 0.432 |
| 315 | 0.80 | 0.159 | 1.50 | 0.162 |
| 316 | 1.8 | 3.60 | 44.1 | 1.82 |
| 317 | 1.8 | 1.80 | 15.3 | 0.797 |
| 318 | 1.8 | 0.90 | 8.50 | 0.391 |
| 319 | 1.8 | 0.358 | 7.00 | 0.183 |
| 320 | 1.8 | 0.182 | 5.00 | 0.081 |
| 321 | 3.5 | 3.50 | 48.8 | 0.886 |
| 322 | 3.5 | 1.75 | 34.3 | 0.407 |
| 323 | 3.5 | 0.693 | 20.7 | 0.169 |
| 324 | 3.5 | 0.350 | 17.5 | 0.095 |

* the in situ contents were not measured because of the variable flow pattern.

# APPENDIX C

## CALCULATED DATA

CALCULATED DATA

Sample calculations are presented for the Reynolds number, the Fanning and modified friction factors and the holdup ratio.

The calculated modified friction factors and holdup ratios are presented for the 6.29 cp. viscosity oil in Table C1, the 16.8 cp. viscosity oil in Table C2 and the 65.0 cp. viscosity oil in Table C3.

Sample Calculations

(1) Conversion of lb. per min. to ft. per sec.

For both water and the three test oils

1 lb. per min. = 0.0454 ft. per sec.

(2) Calculation of Reynolds number.

$$Re = \frac{\rho v d}{\mu}$$

$$= \frac{62.2 \quad 3600 \quad 1.040}{12 \quad 2.42} \left(\frac{v}{\mu}\right)$$

where v is in ft. per sec.

and $\mu$ is in centipoise.

For $\mu$ = 0.894 cp. (water) Re = 8990 v

= 6.29 cp. Re = 1280 v

= 16.8 cp. Re = 477 v

= 65.0 cp. Re = 124 v

(3) Calculation of friction factors.

$$\text{Fanning friction factor} = \frac{\Delta P d g_c}{2 \Delta L \rho v^2}$$

$$= 0.00484 \frac{\Delta P}{v^2}$$

where $\Delta P$ = pressure drop over test section (inches of water)

and v = liquid velocity (ft. per sec.)

Modified friction factor based on the water properties

$$= \frac{\Delta P d g_c}{2 \Delta L \rho_w v_w^2}$$

$$= 0.00484 \frac{\Delta P}{v_w^2}$$

where $\Delta P$ = pressure drop over test section (inches of water)

$v_w$ = superficial water velocity (ft. per sec.)

(4) Holdup ratio

$$H_R = \frac{\text{input ratio, } R_v}{\text{in situ ratio}}$$

for example in experiment 210

$$H_R = \frac{0.500}{0.428} = 1.17$$

TABLE C1

CALCULATED DATA FOR 6.29 cp. VISCOSITY OIL

| Experiment number | Input oil-water ratio | Holdup (1) | ratio (2) | Average holdup ratio | Modified friction factor |
|---|---|---|---|---|---|
| 101 | 10.0 | 1.17 | 1.07 | 1.12 | 1.50 |
| 102 | 5.13 | 2.21 | 2.02 | 2.11 | 0.193-0.386 |
| 103 | 2.11 | 1.29 | 1.21 | 1.25 | 0.353 |
| 104 | 1.04 | 1.45 | 1.34 | 1.39 | 0.193-0.291 |
| 105 | 0.455 | 0.882 | 0.853 | 0.868 | 0.193 |
| 106 | 10.0 | 0.98 | 0.97 | 0.975 | 1.24 |
| 107 | 4.97 | 0.99 | 0.985 | 0.988 | 0.377 |
| 108 | 2.05 | 1.49 | 1.42 | 1.46 | 0.0574 |
| 109 | 0.985 | 1.29 | 1.25 | 1.27 | 0.0377 |
| 110 | 0.515 | 1.28 | 1.26 | 1.27 | 0.0161 |
| 111 | 4.92 | 1.10 | 1.09 | 1.10 | 0.296 |
| 112 | 2.00 | 1.34 | 1.27 | 1.31 | 0.0536 |
| 113 | 1.01 | 1.26 | 1.25 | 1.26 | 0.0226 |
| 114 | 0.514 | 1.22 | 1.22 | 1.22 | 0.0129 |
| 115 | 0.194 | 1.20 | 1.20 | 1.20 | 0.00868 |
| 116 | 2.00 | 1.13 | 1.11 | 1.12 | 0.0388 |
| 117 | 0.986 | 1.30 | 1.25 | 1.28 | 0.0216 |
| 118 | 0.505 | 1.27 | 1.27 | 1.27 | 0.0127 |
| 119 | 0.202 | 1.26 | 1.21 | 1.24 | 0.00940 |
| 120 | 0.106 | 1.31 | 1.27 | 1.29 | 0.00806 |
| 121 | 1.00 | 1.18 | 1.15 | 1.17 | 0.0174 |
| 122 | 0.507 | 1.29 | 1.24 | 1.27 | 0.0113 |
| 123 | 0.200 | 1.19 | 1.15 | 1.17 | 0.00774 |
| 124 | 0.097 | 1.20 | 1.14 | 1.17 | 0.00687 |

TABLE C2

CALCULATED DATA FOR 16.8 cp. VISCOSITY OIL

| Experiment number | Input oil-water ratio | Holdup ratio | Modified friction factor |
|---|---|---|---|
| 201 | 10.0 | 1.50 | 1.21 |
| 202 | 5.00 | 1.66 | 0.484-0.568 |
| 203 | 2.00 | 1.28 | 0.218 |
| 204 | 1.00 | 1.05 | 0.145 |
| 205 | 0.50 | 1.17 | 0.145 |
| 206 | 10.0 | 0.826 | 0.948 |
| 207 | 5.00 | 1.53 | 0.185 |
| 208 | 2.00 | 1.29 | 0.0376 |
| 209 | 1.00 | 1.29 | 0.0188 |
| 210 | 0.50 | 1.17 | 0.0188 |
| 211 | 4.98 | 1.26 | 0.159 |
| 212 | 2.00 | 1.35 | 0.0543 |
| 213 | 1.00 | 1.19 | 0.0193 |
| 214 | 0.50 | 1.08 | 0.0121 |
| 215 | 0.199 | 1.12 | 0.00833 |
| 216 | 2.00 | 1.18 | 0.0583 |
| 217 | 1.00 | 1.26 | 0.0212 |
| 218 | 0.50 | 1.14 | 0.0130 |
| 219 | 0.199 | 1.15 | 0.00926 |
| 220 | 0.101 | 1.06 | 0.00776 |
| 221 | 1.00 | 1.07 | 0.0158 |
| 222 | 0.50 | 1.23 | 0.0108 |
| 223 | 0.198 | 1.06 | 0.00773 |
| 224 | 0.100 | 1.07 | 0.00690 |

TABLE C3

CALCULATED DATA FOR 65.0 cp. VISCOSITY OIL

| Experiment number | Input oil-water ratio | Holdup ratio | Modified friction factor |
|---|---|---|---|
| 301 | 10.0 | 0.522 | 19.05 |
| 302 | 5.0 | 0.626 | 7.20 |
| 303 | 2.0 | 0.637 | 2.07 |
| 304 | 1.0 | 0.630 | 1.93 |
| 305 | 0.5 | 0.434 | 0.93 |
| 306 | 10.0 | 0.512 | 4.77 |
| 307 | 5.0 | 0.612 | 2.69 |
| 308 | 2.0 | * | 0.306-1.15 |
| 309 | 1.0 | 1.24 | 0.0375 |
| 310 | 0.5 | 1.12 | 0.0214 |
| 311 | 4.98 | 0.638 | 1.13 |
| 312 | 2.00 | 1.04 | 0.0625 |
| 313 | 1.00 | 1.30 | 0.0215 |
| 314 | 0.50 | 1.16 | 0.0147 |
| 315 | 0.199 | 1.23 | 0.0113 |
| 316 | 2.00 | 1.10 | 0.0656 |
| 317 | 1.00 | 1.26 | 0.0228 |
| 318 | 0.50 | 1.28 | 0.0127 |
| 319 | 0.199 | 1.19 | 0.0105 |
| 320 | 0.101 | 1.23 | 0.00746 |
| 321 | 1.00 | 1.13 | 0.0193 |
| 322 | 0.50 | 1.23 | 0.0135 |
| 323 | 0.198 | 1.18 | 0.00819 |
| 324 | 0.100 | 1.05 | 0.00692 |

# APPENDIX D

## MEASUREMENT OF OIL-WATER INTERFACIAL TENSIONS

## MEASUREMENT OF OIL-WATER INTERFACIAL TENSION

The interfacial tensions of the three oils in contact with water were measured by the capillary method described by Bartell and Miller (1). The capillary was contained in one side of the U-tube shown in Figure D1.

### Theory

The height, h, of rise of a pure liquid in a capillary tube of diameter D is given by:

$$h = \frac{4\lambda}{D\rho g}$$

where $\lambda$ = surface tension of the liquid, dynes per cm.

$\rho$ = density of the liquid, gm. per $cm.^3$

g = gravitational acceleration, ft. per $sec.^2$

$$\text{Hence } D = \frac{4\lambda}{h\rho g} \quad . \quad . \quad . \quad (D1)$$

Now, with reference to Figure D1, $h_o$ is the height of the air-oil interface above the oil-water interface in the capillary and $h_w$ is the height of the air-water interface above the oil-water interface. If $\rho_o$ and $\rho_w$ are the densities of the oil and water respectively then a force balance, in which a zero angle of contact is assumed for the oil-water interface at the capillary wall, gives:

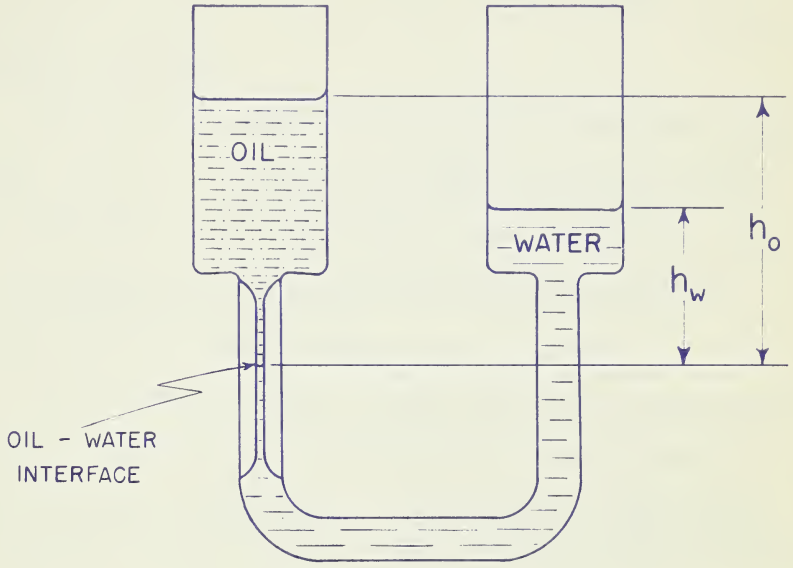



FIGURE DI

U-TUBE USED IN MEASUREMENT OF INTERFACIAL TENSIONS

$$\frac{h_w \rho_w \pi D^2 g}{4} + \lambda' \pi D - \frac{h_o \rho_o \pi D^2 g}{4} = 0$$

where $\lambda'$ = oil-water interfacial tension, dynes per cm.

if $\rho_o = \rho_w = \rho$ then:

$$\lambda' = \rho \frac{Dg}{4} (h_o - h_w) \quad . \qquad (D2)$$

Experimental Procedure

Pure water, pure benzene and the benzene-water system were used as standards to experimentally determine the diameter of the capillary. The standards used in this determination are given in Table D1 and the results are given in Table D2.

In the measurement of the oil-water interfacial tensions the U-tube was surrounded by a water bath at 25°C. and burettes were used to feed the oil and water to the different sides of the U-tube. A cathetometer was used to measure the heights of the interfaces. The results obtained in the measurement of the interfacial tensions of the three test oils are given in Table D3.

| System | Density gm./cm.$^3$ at 25°C. | Surface tension dynes/cm. at 25°C. | Interfacial tension dynes/cm. at 25°C. | Reference |
|---|---|---|---|---|
| Water | 0.998 | 71.97 | | (5) |
| Benzene | 0.878 | 28.25 | | (1) |
| Benzene -water | | | 34.60 | (1) |

Table D1. Standards used in the determination of capillary diameter.

| System | Capillary rise | $h_b \rho_b - h_w \rho_w$ | Capillary diameter from equation (1) |
|---|---|---|---|
| | cm. | | |
| Water | 3.405<br>3.405<br>3.410<br>3.380 | | 0.0866 |
| Benzene | 1.535<br>1.530<br>1.445 | | 0.0882 |
| Benzene -water | | 1.584<br>1.594<br>1.603 | 0.0886 |

Average capillary diameter = 0.0880 cm.

Table D2. Results in determination of capillary diameter.

| System | $(h_o-h_w)$ | Average $(h_o-h_w)$ | Interfacial tension from equation (2) |
|---|---|---|---|
| | cm. | cm. | dynes per cm. |
| 6.29 cp. oil-water | 1.980<br>2.100<br>2.055 | 2.045 | 44.1 |
| 16.8 cp. oil-water | 2.080<br>2.010<br>2.115 | 2.068 | 44.5 |
| 65.0 cp. oil-water | 1.43<br>1.35<br>1.34 | 1.38 | 29.7 |

Table D3. Results in determination of oil-water interfacial tensions.

Conclusions

The diameter of the capillary = 0.0880 cm.

The interfacial tensions of the 6.29, 16.8 and 65.0 cp. viscosity oils in contact with water = 44.1, 44.5 and 29.7 dynes per cm. respectively.

## NOMENCLATURE

$d$ = diameter of pipeline, ft.

$D$ = diameter of capillary, cm.

$f$ = Fanning friction factor, dimensionless

$f_w$ = modified friction factor based on water properties, dimensionless

$g_c$ = dimensional conversion factor, $lb_m$. ft. per $lb_f$. $sec.^2$

$h$ = liquid height, cm.

$H_R$ = holdup ratio, ratio of input oil-water ratio to in situ oil-water ratio, dimensionless

$\Delta L$ = length of pipeline, ft.

$\Delta P$ = pressure drop, lb. per $ft.^2$

$Q$ = volumetric flow rate, $ft.^3$ per sec.

$R$ = pipeline radius, ft.

$r_i$ = radius of oil-water interface in concentric flow, ft.

$R_v$ = input oil-water volume ratio, $ft.^3$ per $ft.^3$

$Re$ = Reynolds number, dimensionless

$v$ = superficial liquid velocity, ft. per sec.

$\lambda$ = surface tension, dynes per cm.

$\lambda'$ = interfacial tension, dynes per cm.

$\mu$ = liquid viscosity, $lb_m$. per ft. sec.

$\rho$ = liquid density, $lb_m$. per $ft.^3$

Subscripts: b = benzene

f = force

m = mass

o = oil

w = water

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